Coordinated Volt/Var Control in Smart Distribution System with Distributed Generators

by

Fatima Binte Zia

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2015

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The high penetration level of Distributed Generation (DG) is one of the most attractive features of the smart grid aside from being automatic, modern, reliable and efficient. However, high penetration comes with more challenges to deal with such as the voltage and reactive power (Volt/Var) control and increased power loss. To address the issues in incorporating DGs in the power distribution system, this thesis provides a closer look at the Volt/Var control and power loss concerns caused by the random behavior of DGs. Modifying conventional control techniques by moving to a smart technique is a core requirement to mitigate these issues. Voltage control is hard if it is solely handled by on load tap changer (OLTC) transformer and switched shunt capacitors (SC) due to the high penetration and unpredictable behaviors of DGs. The ability to inject the reactive power of the DGs with the proper coordination of SC and OLTC can contribute to control Volt/Var besides minimizing the power loss. Centralized or distributed control of the Volt/Var control device integrated with heuristic based control scheme can be a promising solution to this problem.

The distributed control scheme based on the automated agent technology is the first solution to the Volt/Var control problem presented in this thesis. . This is also known as the multi-agent based system. Each device, i.e. OLTC, DG unit, SC and loads have their own intelligent agents which are capable of optimizing their operations via local measurements and communications with other control agents. Assuming the existence of proper communication medium and protocols, each agent without the knowledge of the whole system, can contribute to control Volt/Var. While doing so, none of the agents are going to violate their own requirements while attaining the global objective of Volt/Var control and reducing total system loss. The proposed control scheme for Volt/Var control is tested and simulated using the 8 bus distribution system in Matlab/Simulink. Fuzzy logic controller for each agent is used based on predefined rules. It was found that the voltage profile is improved after

coordinating all the control devices with DGs. The number of tap operations for OLTC is also reduced after the coordination resulting to its increased lifetime.

In the second part of this thesis centralized genetic algorithm based control mechanism is introduced in the system. In this section OLTC and SC are treated as controllers and DGs are treated as PQ bus. To get optimum voltage and realize reactive power control, the second part shows 24 hours lead time coordination among the OLTC, SC and DGs. This coordination takes place utilizing genetic algorithm. The optimal number of switching during the 24-hour period for both SCs and OLTCs is determined with the goal to control reactive power flow or minimize the power loss, and above all to keep the voltage profiles within acceptable levels. The functionality of the proposed technique is tested through the simulation of a 30-bus system in Matlab. Findings from the simulation results showed that the DG operation no longer imposes a significant effect on the voltage fluctuations and power loss profile in the distribution system if the OLTC and SC are switched based on a 24-hour forecasted data of the DGs. The adaptive control technique which updates switching time and number every 6 hours of the day gives a better loss profile since the forecasted data becomes more accurate with time. This approach is simple, straightforward and efficient.

Acknowledgements

All praise for Allah and His immense mercy on me and my family and for giving me all the strength to accomplish my goal. Besides that I am obliged to the following individuals as well for their help and backing me all the time.

My sincere gratitude to my supervisor and mentor Professor Ehab El-Saadany for his patient guidance all throughout my master's program. I learned the true meaning of getting into a research and think as a researcher. He had shown me path during all difficult phases and had been generous enough to listen and understand me. Thank you for enduring me in the course of the keep going two years while I was experiencing heaps of ups and down

My gratitude to Professor Hany E. Farag cannot be expressed in words. He has observed my work very closely and gave his constructive comments. He has always managed time for discussing my problems and taught me how to generate new research ideas, which amplified my research skills.

To my parents- I'll never tell but thank you. There was not a single day I did not hear from you. Thank you for supporting me when life was not in our favor. You are my real life hero. Thank you for listening to me when I was all alone here. Thank you for those wonderful words which motivated me, helped me to handle the work loads. To my spouse– thank you for respecting my decision of pursuing MASc at University of Waterloo and enduring my frustration. Although we were thousand miles away, you nurtured and kept the bonding alive.

To all my research group members – thank you for your friendship, fruitful discussions and constant support. Special thanks to Elham for being my elder sister and taking care of me.

Dedication

I would like to dedicate my work to my parents and my soul mate

- They are my true inspiration and strength.

Table of Contents

List of Figures

List of Tables

Nomenclature

Indices

B	Total number of bus
K	Number of OLTC
S	Number of SC

Parameters

V_{LB}	Lower boundary votlage
V_{UB}	Upper boundary voltage
I_R	Real component of current
I_X	Reactive component of current
I_{ce}	Current due to shunt capacitor
V_{DG}	DG bus voltage,
V_i	Voltage at bus 'i'
P_{DG}	DG generated real power
Q_{DG}	DG generated reactive power
P_R	Injected real power
Q_R	Injected reactive power
P_L	Reactive load power
Q_L	Reactive load power
S_R	Injected apparent power,
R	Resistance transmission line
X	Reactance of the transmission line
I_R	Represents injected current
V_j^{lb}	Maximum voltage for bus number j
V_j^{ub}	Minimum voltage for bus number j
T_j^{lb}	Minimum number of tap change allowed for a day for OLTC j
T_j^{ub}	Maximum number of tap change allowed for a day for OLTC j
T_j	Total tap change occurred for OLTC j
C_j^{lb}	Minimum number of switching allowed for a day for shunt capacitor j
C_j	Total switching occurred for capacitor j
C_j^{ub}	Maximum number of switching allowed for a day for shunt capacitors j

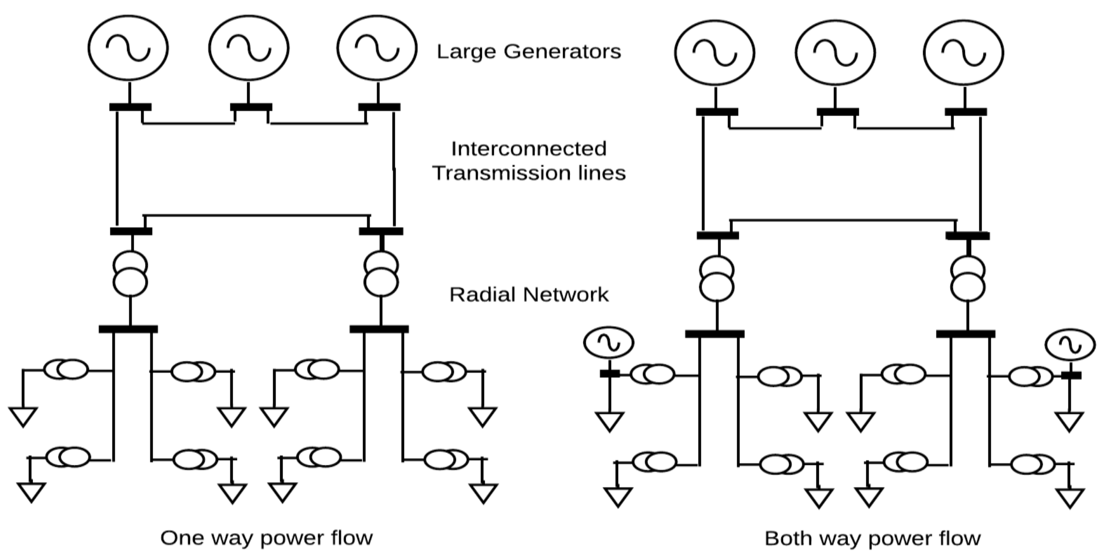
Chapter 1
Introduction

1.1 Overview

The power distribution system is a core part of the electric grid which links transmission systems and end users or the consumers. Environmental impact, rise of energy demand, dependence on traditional fossil fuel plants are very concerning energy issues today. The development of renewable energy resource technologies allows researchers to perceive renewable energy resources as a supplement to existing power resources. In the near future it is also expected that the use of renewable energy resources will increase to meet growing power demands [1]. Generators connected to distribution systems are known as distributed generators (DG). Although it is known that distribution systems are planned, designed and constructed to provide electric power to the end users or consumers, the integration of DGs introduces changes to existing networks. Power generated by DGs is not related to the load demand of that network. Therefore the connection of DGs makes the network more active and dynamic due to their properties. As power is transmitted through the distribution system some power loss may occur during the transmission. Without DGs, voltage control in the distribution system is traditionally performed by a passive approach where the power flow is unidirectional. However, DG integration may cause bidirectional power flow. DGs have low impact on the environment which serves as one of its positive attributes. Allowing the connection of more DGs in the existing distribution network may reduce our dependence on traditional generation resources [2]. Line resistance, challenges with over-voltage and under-voltage in distribution networks have to be dealt with in using DGs in the system. Hence, a well-designed voltage control method is a priority to maintain the voltage level within the allowable boundary. On-load-tap-changer (OLTC) and Capacitor Banks are conventional Volt/Var control devices used in power distribution systems. As DGs come with their random output nature, good coordination among the traditional voltage control devices such as OLTC and shunt capacitors (SC) and DGs is necessary to obtain permissible voltage level. The primary goal of Volt/Var Control in the distribution system must aim to restrict the voltages within a required range under different operating conditions such as the load variation and random output.

1.2 Volt/Var Control in Distribution Systems with DGs

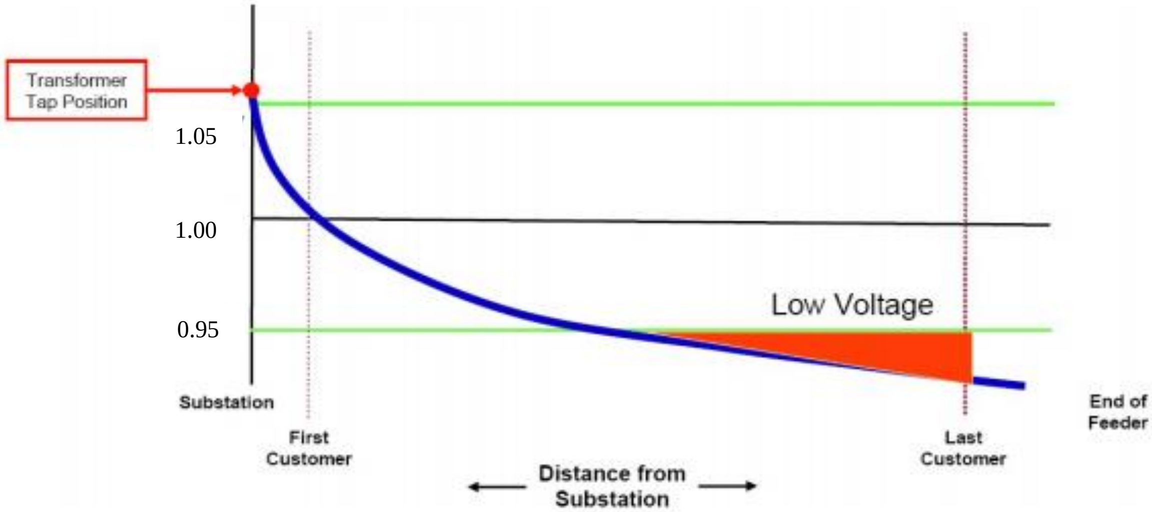
DG technologies are varied in types. Examples are solar photovoltaic, wind turbines, fuel cells, biomass, small gas turbines, geothermal plants and micro turbines etc.[3]-[5]. Figure 1-1 (a) shows



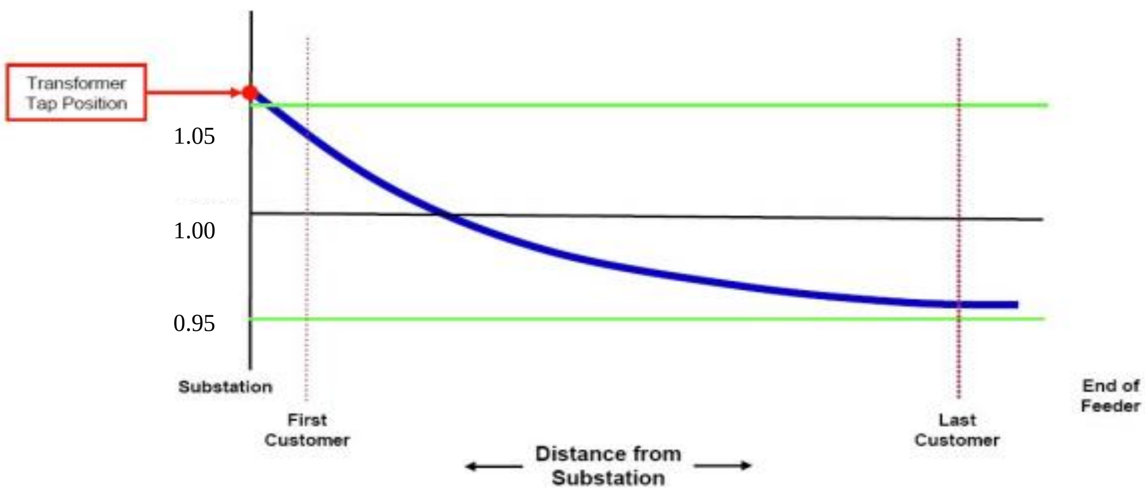
(a) (b)

Figure 1-1 Traditional Power System (left) and modern Power System with DGs (right) [6]

a traditional distribution system and (b) a modern distribution system with DGs. The most certain effect of DGs on an existing distribution system is the change in power flow direction and system operation. This indicates that control demands necessary actions to mitigate the influences. In a conventional distribution system, the substation provides the power and voltage drop is impacted by the length of the feeder. To fix this issue the usual step is to increase the substation voltage to keep



(a)



(b)

Figure 1-2 Without Volt/Var Control (a) Heavy Load (b) Light Load [7]

the downstream voltage level within limits during heavy load. However, the same setting may cause over voltage if loading is lighter. In Figure 1-2 an example is given to show the difference on a different loading condition at a particular tap setting at the substation. The equipment used to handle the voltage regulation problem are OLTC, SC, synchronous condenser, static var compensator etc. In this thesis the impact of solar and wind power generation on voltage and reactive power control is studied. The target is to find a method which ensures elimination of voltage violation and to keep the switching of shunt capacitors and load tap changers within limit to maximize their lifetime, and hence minimize power loss.

1.3 Research Objectives

A literature review is conducted in chapter two to survey the impact of DGs on the voltage profile of the distribution system, the loss profile and reactive power control. The objective of this thesis is motivated by the problems found in the survey with possible solutions to mitigate them. From the many given questions on the survey, this thesis has chosen six problem descriptions listed below:

1. How is the switching of tap-changer and shunt capacitors affected due to the presence of DGs in the network? Up to what level do DGs affect the lifetime of OLTC and shunt capacitors?
2. How is voltage and loss profile affected by the presence of DGs?
3. How does coordination among OLTC operation, SC and DG help improve loss and voltage profile?
4. To what extent would a coordinated OLTC and SC operation influence network losses?
5. How could a centralized/ decentralized control with DG improve the voltage and loss profile?
6. Can the difference between fixed and adaptive (time based) control strategy influence network losses?

1.4 Organization of Thesis

Chapter 1: The first chapter introduces the thesis. This chapter highlights the gap to be analyzed in the following chapters. The chapter provides an overview of the power distribution system indicating the possible negative and positive impacts of DGs on the system. It also introduces the objective of this thesis.

Chapter 2: This chapter is a literature review which helps to understand the problem addressed in this thesis. It covers the previous works done by researchers and the scope of new research being made on the problems presented. A brief introduction of DGs is given, followed by the nature and system requirements to include DGs in the network. The impact of DGs on the power system, mainly focusing on voltage and loss gap of the system is then discussed. The number of operations for Volt/Var regulating devices is a priority in this thesis. The varied techniques used in past literature to address the Volt/Var problem are thoroughly studied. From this information a summary is given at the last part with an argument for possible problem description.

Chapter 3: A fuzzy based method for Volt/Var control for optimal dispatch of OLTC and optimal setting of SC is proposed in this chapter. An introduction to fuzzy based systems followed with an explanation on why this method is chosen to solve Volt/Var control problem is discussed. A multi-agent based control is introduced in the following section. After this, a detailed operation method for the controller is described. All the members of the system are described with their functioning steps. Coordination method among the agents is shown next. Simulation results verifying the methods' functionality is given at end of this chapter for verification.

Chapter 4: Genetic algorithm based Volt/Var control for optimal OLTC and SC dispatch in the presence of DG is presented in this chapter. A brief introduction of GA with its components and features are described at the beginning of this chapter. Optimization technique using GA is described. Power flow algorithm chosen for radial network and control method is also described here. Several cases are analyzed on how particular penetrations of DG impact the test system. In Case 1 the test system is analyzed without the presence of DG, OLTC and SC. Results are compared with this scenario as it does not have any control. In Case 2 the test system includes SC and DGs to show how DGs affect the total switching number of SC for over a month. In case 3 the test network topology is modified by introducing OLTC at the substation. A mixed type of DGs at various locations of the test system is also introduced to verify how GA based control give optimal dispatch setting for the 24-hour period. Test case 4 is modified to use adaptive control instead of day-ahead control and is used to verify the improvement of power loss profile and voltage profile. A brief discussion of the results are presented at the end of this chapter.

Chapter 5: Analysis of the simulation results is found in this chapter. Few conclusions are drawn in this chapter. At the end of this chapter a direction to the future continuation of this work is presented. Appendix presents data for test systems and provides Matlab codes to run the problem with proposed methods.

Chapter 2
Literature Review

2.1 Distributed Generator

The current trend to meet increased power demand is to add Distributed Generation (DG) in the existing power distribution system. Incorporation of DGs requires many technologies and new devices in the system. Other countries use different terminologies in place of DGs such as “embedded generation”, “dispersed generation”, “decentralized generation”, etc. Additionally, the definition of DGs also varies among different organizations. This causes some mismatch on the terminology used and definition of DGs. However, for this thesis, DGs will be defined as the electric source proximate to the customer level and connected to distribution lines that are connected to the power system. The size and power generation of these DGs are very small compared to our traditional power generation resources [8].

2.2 System Requirement and Regulations

As discussed before, the influence of distributed generation (DG) on the distribution network’s quality cannot be ignored. Before proposing any method a standard will help set the parameters and constraints to meet the requirement. IEEE Stands 1547 [9] has requirements about how much voltage violation is allowed with or without the presence of DGs. Voltage variations must lie within the permissible limit and compared with the nominal voltage at the point of the distribution network where DGs are connected [9]. The integration of DG is likely to have a significant impact aside from affecting the system profile and the operation challenges.

2.3 Connecting Distributed Generator in the Radial Network

The distribution network supplies electric power to the end user of the feeder from the substation. A simple model of a radial distribution network is demonstrated in Figure 2-1. It has a stiff grid, transmission lines, transformers and loads. Power losses occur due to the resistance of transmission lines and other factors.

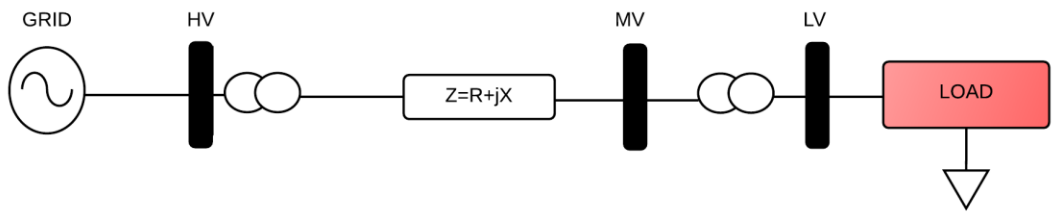


Figure 2-1 Radial distribution network

When distributed generators are connected to a distribution network it can simply be shown like Figure 2-2. Power flow in the network is dependent on the size and location of the DGs and also on load demand at a specific time.

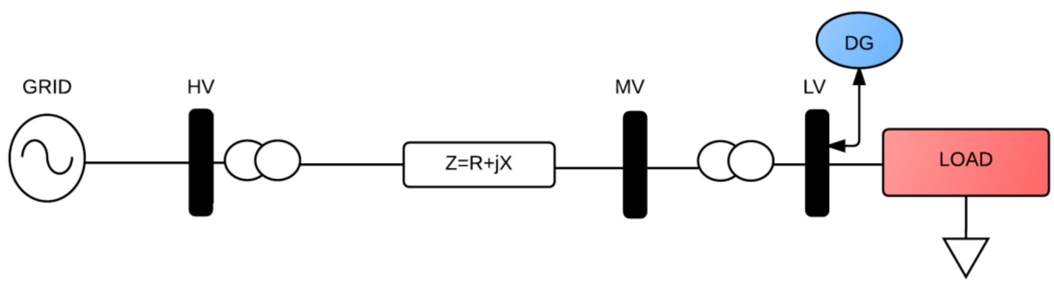


Figure 2-2 Radial distribution network with DG

2.4 Volt/Var control in Distribution Networks

The main purpose of regulating voltage in a distribution system and controlling reactive power is to reduce system loss [11]. The conventional way of controlling Volt/Var in the distribution network is done by using OLTCs, SCs, and voltage regulators at various locations of the feeder. These devices are very reliable and efficient to control Volt/Var until the start of integration of DGs.

2.4.1 On-Load Tap Changing Transformers

On-Load Tap Changing Transformers (OLTC) are used to regulate or maintain the voltage within the limits. Using the substation as a main source of power may help OLTCs provide electric power to the distribution network. Most distribution transformers have tap changers which regulate the voltage by changing the tap. Turns ratio is regulated on the primary and secondary side. A typical OLTC has 8 to 16 taps with a step size of 1.5% voltage variation. In total, one OLTC has the capability to control the voltage to the range of $\mp$12 percent [12]

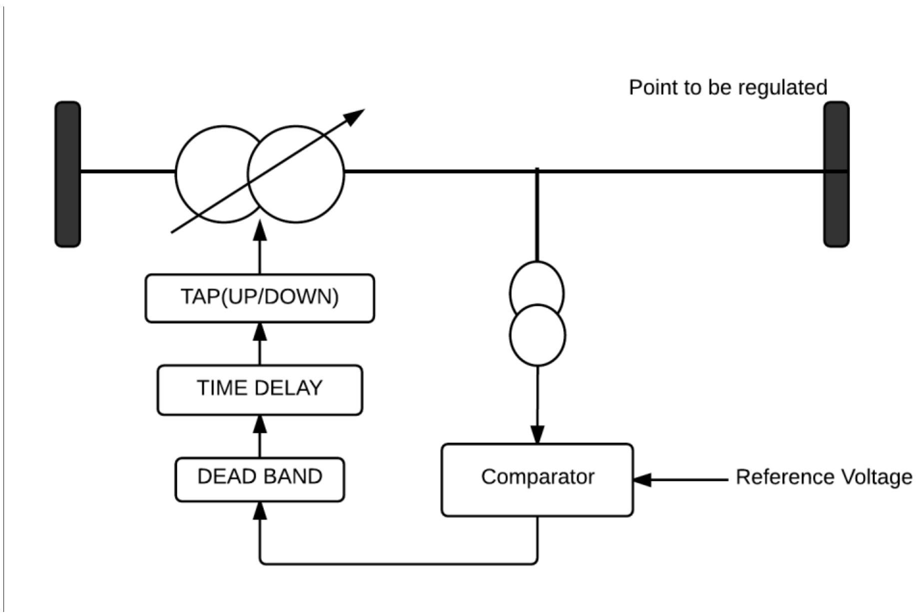


Figure 2-3 OLTC Basic Setup

Loads located at the downstream of the network are more likely to experience voltage drop. In such scenarios OLTCs are likely to raise the voltage by changing the tap to an appropriate level. Figure 2-3 shows a very basic arrangement for OLTC. It keeps the secondary voltage V within the limit as given below:

$$V_{LB} \leq V \leq V_{UB}$$

OLTC is normally provided with an LDC feature built in it. This feature keeps the remote bus voltage within limit. In practice, the LDC function is disabled to keep the operation simplified and also to keep the OLTC free from the effect of X/R ratio of the line.

2.4.2 Shunt Capacitors

Shunt capacitors inject reactive power at the location it is placed in the distribution system. Reactive power injected into the distribution network boosts the voltage by mitigating reactive power demand. Shunt capacitors are added to distribution networks to boost voltage levels. These capacitors also neutralize the effect created due to of inductive loads [13]. Voltage drop of the transmission line in a distribution system can be expressed with the following equation:

$$Voltage\ drop = jI_X X_L + I_R \qquad (1)$$

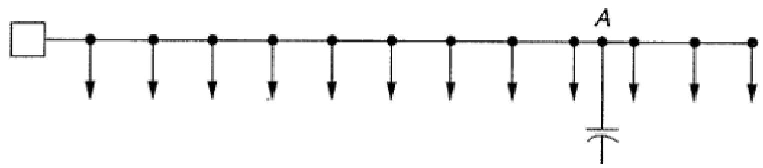
A capacitor puts following impact on line voltage dropped as expressed in equation (2)

$$Voltage\ drop = jI_X X_L + I_R R - jI_C X_L \qquad (2)$$

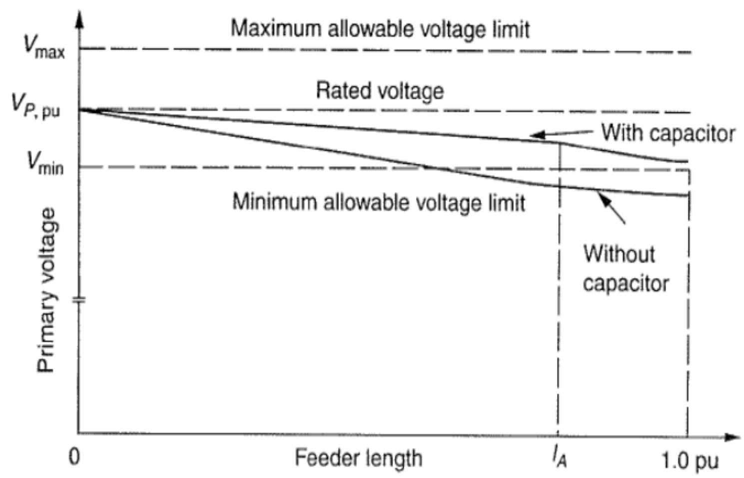
From equation (1) and equation (2) it can be said that a capacitor in the distribution line can increase the voltage according to equation (3):

$$\text{Regulated voltage} = I_C X_L$$

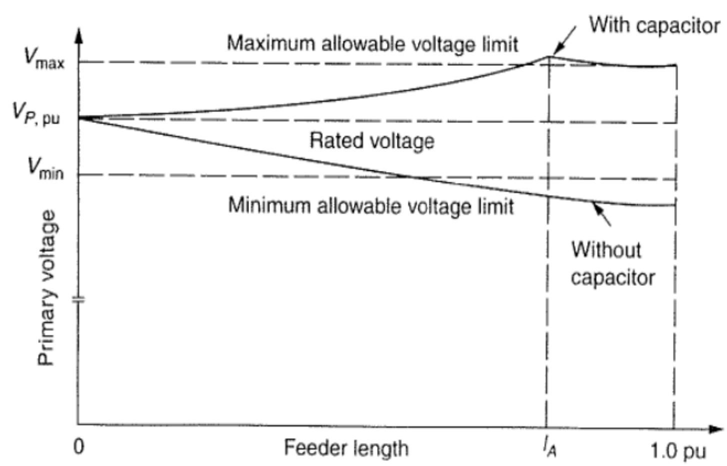
Thus, adding capacitor banks in the network can boost system voltage and help keep it within desirable limits. Optimized voltage profile can be achieved by controlling the magnitude of reactive power injected by such capacitors. Capacitor banks are set in a distribution network to correct the power factor of the load [14]. Installed capacitors can either be fixed or switched. In this thesis we are going to discuss switched shunt capacitor. Figure 2-4 [14] shows the effect of a capacitor on the



(a)



(b)



(c)

Figure 2-4 Effect of capacitor on the voltage profile of: (a) uniformly distributed load feeder with a capacitor; (b) voltage profile with capacitor (heavy load); and (c) voltage profile with capacitor (light Load) [14]

distribution network during heavy and light loading conditions. When the feeder experiences leading power factor, a fixed capacitor can cause over voltage. Fixed capacitors are used to fulfill the minimum reactive power requirement and place where minimum voltage lift is needed. Meanwhile, switched shunt capacitors are used to handle larger voltage fluctuation and can be turned off or on during heavy or light loading conditions. The switched capacitor can be controlled manually or by using an automated mode. Conventionally switched shunt capacitors are switched based on time, voltage controlled, time controlled, current controlled and temperature controlled and power factor control scheme [14].

2.5 Impact of Distributed Generation

Distribution systems are planned and designed considering transmission line parameters, loads and generation capability. When DGs are introduced in the distribution system without any action taken, it might have a significant impact on the system power flow and voltage profile. Based on the location, the size of the DGs also depends on the load profile which can bring both positive and negative impacts [15]. This thesis focuses on the impact of DGs on system voltage and loss profile and the impact of the number of switching of shunt capacitor and OLTCs. The best way to analyze this effect is to test a distribution system using a simulating tool like e.g. Matlab with or without DGs. The results obtained from the investigation can give an overview of the problem. This investigation will be carried out thoroughly to determine the effects and solutions.

2.5.1 Impact of DG on Voltage Profile

Radial network regulates the voltage with the help of OLTC, SC and line regulators. Regulation occurs considering the power flow is unidirectional. The connection of DG, if operated at leading power factor mode, may increase the voltage by adding reactive power to the network. The direction and magnitude of real and reactive power might alter based on DG location and size [16-17]. Due to uncoordinated operations for regulation more challenges may arise such as power loss increment and number of switching increment. Interaction between DG and OLTC and the influence of OLTC on DG have a lot of importance.

Consider the following figure 2-5 [18] as simple two-bus network with DG. It can be written that this network has a transmission line, load, reactive power support source, DGs (solar or wind).

Impedance $Z=R+jX$.

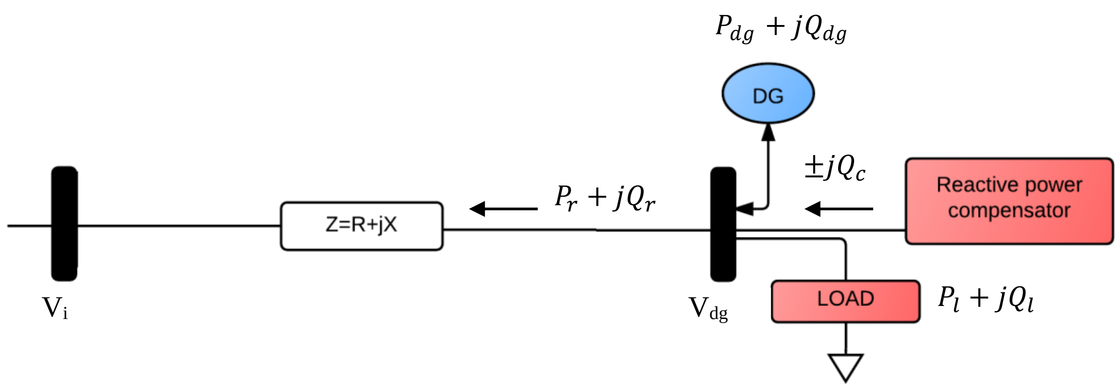


Figure 2-5 Simple Two Bus Network with DG

Total injected power

$$S_r = P_r + jQ_r \tag{3}$$

$$S_r = P_{dg} + jQ_{dg} + jQ_c - P_l - jQ_l \tag{4}$$

$$S_r = P_{dg} - P_l + j(Q_{dg} + Q_c - Q_l) \tag{5}$$

It can also be written as following

$$S_r = I_r^* V_{dg} \tag{6}$$

$$S_r^* = I_r \, V_{dg}^* \tag{7}$$

From equation (1) and 6) we can write

$$I_r = (P_r - jQ_r)/V_{dg}^* \qquad (8)$$

Therefore

$$V_{dg} = V_i + ZI_r \qquad (9)$$

From equation (7) and (8)

$$V_{dg} = V_i + (P_r - jQ_r)Z/V_{dg}^* \qquad (10)$$

$$V_{dg} = V_i + (P_r - jQ_r)(R + jX)/V_{dg}^* \qquad (11)$$

$$V_{dg} = V_i + \frac{(RP_r + XQ_r)}{V_{dg}^*} + j * (XP_r - RQ_r)/V_{dg}^* \qquad (12)$$

Thus the imaginary part of equation (11) above can be neglected as V_{DG} and source voltage has small phase angle.

$$V_{dg} \cong V_i + \frac{(RP_r + XQ_r)}{V_{dg}^*} \qquad (13)$$

Considering reactive power from the compensator above equation can be written again as:

$$V_{dg} \cong V_i + \frac{(RP_r)}{V_{dg}^*} = V_i + \frac{R\left(P_{dg} - P_l\right)}{V_{dg}^*} \qquad (14)$$

Equations (3)-(14) are derived to calculate the voltage at the location where the DG is connected. [18]. Looking at equation (14) it can be said that a constant load voltage at the point where the DG is connected will increase with the increment of real power injected by DGs. When the network experience minimum load, if the DGs are generating maximum power; system might experience over voltage at buses. Considering the maximum or minimum load of the network the DG penetration level is decided.

2.5.2 Impact of DG on Losses

Distributed generators have a significant impact on the loss profile of the distribution feeder. The location of DG is mainly responsible for the increased or decreased loss profile. DG can be compared with SC when it comes to loss reduction. [19]. Capacitor improves voltage and reduced losses by injecting reactive power. Meanwhile, DGs have the capability to inject real power besides injecting reactive power. There are many methods in literature which show how to find the optimal allocation of the DGs. It is understood from the literature that whenever the distribution feeder has high losses, a large number of small DG placement can reduce the losses to a great extent. Larger capacity DGs can be added after evaluating the feeder capacity [19].

2.5.3 Impact of DG on Number of Operation

Tap Change or the switching of OLTC or SC is counted as number of operations which impacts the lifetime of the device. A voltage regulating device with less tap changes during its operations would have longer lifetime, making the Volt/Var control scheme more efficient. This thesis focuses on the reduction of the number of operations of OLTC and SCs to ensure that DGs do not contribute in shortening the lifetime of these devices. Many research has been found in literature done to address tap operation and maintenance of OLTC. Old fashioned mechanical switches are the major part of OLTC. These switches has been replaced by power-electronics as shown in [38]. Thyristor assisted OLTC have been proposed in [39] where current is diverted through the mechanical switched using power electronics. Author of paper [40] presents another innovative method to reduce wear and tear of OLTC by tuning the existing rule for OLTC controllers. Cascaded OLTCs are controlled by decentralized method using fuzzy logic and adaptive control in paper [41]. Capacitor control in radial distribution network with coordinated OLTC by centralized control has been treated in [42].This method is based on full non-linear power flow formulation and similar to Volt/Var control method having real time simulation as presented in [43]. Field test result of this research is shown in [44].

Modification of this research work including effects of other local controller of distribution system is done in [45]. A linearized system model, centralized information and variable structure control for coordinated OLTC is described by authors of [46]. OLTC modeling issue, OLTC coordination with aggregated load got attention in [47]-[51]. Voltage problem due to OLTCs are analyzed in [52]-[54]. Stability concerns for OLTC is described in [55]-[56]. Voltage instability problem and coordination of OLTC and load tap interactions were investigated in [57].

2.6 Previous Work on Volt/Var Control in Distribution Network with DGs

Automatic voltage control is commonly used in conventional distribution feeders to maintain voltage level. The secondary side voltage of the OLTC is monitored and compared with a reference voltage and action is taken based on the mismatch found. Regulation standard is followed to avoid hunting a dead band.

There are two types of control found in the literature - centralized control and decentralized control.

In support of decentralized control, the author [20] mentions that only dispatchable DGs can help control voltage while most renewable energy resources like wind and PV are hard to control. LDC and OLTC are used in this paper to control voltage. [21] Shows DG can operate both in voltage control mode and power factor control mode. The general mode is voltage control mode. However, if the voltage limit violates it switches to PF control mode. [22] Adds generation curtailment mode whenever the previous dual mode is not in effect. This method is claimed to be cost effective with low capital investment. In [23] DG's varying power factor is utilized to control voltage. DGs absorb reactive power and supply real power to increase voltage level. Basically reactive power output is controlled here.

[24] Proposes a method where DGs are controlled based on the reactive power sensitivity of the bus it is connected with. OLTC also sets its own tap to compensate DG effects. Three modes of operation-constant current, constant power factor and constant voltage are introduced in [25]. One of the

interesting finding is that losses are higher in PF control mode in this work. In [26] only DGs take part in controlling the voltage at its bus. The paper considered the response delay of SC and OLTC. No coordination was introduced here. Authors of [27] introduced the division of large feeders into small groups based on the influence of DGs present in the feeder. However all other regulating equipment is ignored in the study.

Few researches focused on centralized control. For example in [28] a hybrid method is described to maximize DG real power capacity. OPF helped to decide the dispatch of DGs. The thermal limit of OLTC, the fault limit at switchgear is taken care of, but the capacitor and reactor or OLTC tap setting is ignored. [29] describes a controller use state estimation for the network. AVC is activated whenever the node voltage crosses its limit. Besides the OLTCs, DGs and other devices are controlled using AVC. This method improves the injected power by the DGs. [30] aims to use a predictive technique to control the generation of reactive power of the DGs in coordination with the OLTC. In [31] a three level control is shown where DG controls its own bus voltage and OLTC, SC, fixed capacitors regulate conventionally [32]. Coordinated controlled based on predefined objective function is demonstrated in [32]. Coordination among OLTC and DGs to mitigate voltage rise and minimize losses is shown. However, it does not consider capacitors [33]. Different load levels at different periods of the day cause the controller's system parameter change. DGs operate at varied power factor modes if necessary. Differential evolution algorithm is used in [34] to set DGs, OLTC and SC output. Optimal reactive power is verified here. [35] Proposes a coordinated control method to Volt/Var control with the objective to reduce losses. [36] Another coordinated control reactive power of DGs in the network. Model predictive control adjusts AVC for each DG. By penalizing each control action this method ensures faster convergence. However, SC and OLTC are ignored.

From the above survey it is important to note the type of distribution system control intelligence used and the type of control architecture chosen. In centralized controllers all system intelligence controls the devices centrally. Meanwhile, in decentralized control, the decision of taking power is spread in the network. These two broadly distinguished architectures have four categories in the distribution control and has been identified:

- Centralized Control: strategy is stored at the central controller. It takes action based on data provided.
- Substation-centered: The substation is usually in the center for all actions, and is to be controlled based on information.
- Decentralized architecture: controllers are situated at various locations of the feeder.
- Coordinated hybrid: this is somewhat between the centralized and fully distributed control architectures.

Standalone Volt/Var control devices are self-operating, alone, takes action immediately using voltage control and reactive power compensation devices. Static voltage regulators are digital controller for voltage control presented in [58] and also emphasized that, a modern voltage controller should be able to collect data and communicate. Drawback of this paper is controllers did not communicate with each other and controllers were not optimum. In [59] compensator circuit design for SVR in presented. This paper shows effective ways for controlling local voltages by keeping secondary side of SVR at constant level. However in reality set point are away from the optimal operating point. In [60] a local power factor compensator is presented. A Var-metric relay has been used here to control capacitor banks. Relay regulates the device based on settings. However this method did not take care of overall reactive power compensation. Microcontroller based power factor controller demonstrated in [61] and controller were designed to be local. This method can bring two capacitor at contradicting situation at critical feeder loading cases. Method presented in [62] describes capacitors control decided by SCADA in every 15 minutes. It is a coordinated control allows real time control. Draw back if this method is rules are predetermined and cannot include changes in distribution network. Voltage regulators actions are not considered while taking decisions for capacitor banks. Distribution SCADA is used in the control in paper [63]. This method deals with apacitor control problem and voltage control problem separately. Although both are sub problem of high level volt/var control. This rule based method however did not achieve the optimal control of distribution system. A computer program behaving like human to control volt/var problem is presented in [64].Having extensive knowledge base, inference engine and distribution SCADA connected with each other; determines the control decisions. Sensitivity tree method is proposed here to control large distribution system. System nonlinearity requires to be low for this system. In [65]-[66] technical and theoretical expertise has been combined to build knowledge based system. The decision engine controls capacitor banks and voltage controllers with checking long capacitors are on, net dollar savings, loss minimization etc. Short coming of this method is network controller can take over the decision maker if necessary. [67] shows expert system interface with SCADA and human operator has major financial benefits. It gives a better solution to network problem and the computational time is also very reasonable. Control of shunt reactive power compensator and transformer tap positions is proposed in [68] with expert system. This method helps to minimize system loss and reduces operation number. Dynamic approach to reduce computational burden is used in [79] for optimization of optimal setting of OLTC and SC.A discrete optimization for SC and OLTC coordination is demonstrated in [80]. Oriented discrete coordinated descent method for volt/var control is studied in [81]. It uses soft constraints as a penalty factor for cost function. Accurate model of the network and very fast power flow is necessary for this method. Drawback of this method is it does not ensure global minima. Many research have been carried out to find capacitor location, size to decrease power losses. In [69]-[71] a better SC planning considering load size, customer load profile has been proposed. It also helps to improve voltage profile. Capacitors should be switched properly with available control strategies. Automated distributed control is proposed in [72]-[75]. Off line control and real time control are two major type of control as shown in [76]. One day ahead dispatch control is proposed in these papers based on load forecast. Real time control aims to control OLTC and SC based on experiences and measurements. Due to weather conditions load patters might change, there are chances of inaccurate operation and therefore loss increment. There are deterministic load patterns as shown in [77].

2.7 Research Motivation

A good number of Volt/Var control techniques already exist in literature. With proper communication and strong control strategies Volt/Var control can be done using the centralized control. It is not feasible to engage all equipment of the network for controlling because it may cause conflicts and complexity. Additionally, real time control is a significant issue with the random nature of DGs. It is highly encouraged in the literature to keep the control strategy fairly simple and reasonable. In decentralized control, communication is not as important as it is in centralized control. Besides it is fairly simple to implement compared to real time simulation. However coordination becomes very complicated in decentralized control and needs attention. The increasing load demand and the random output nature of DGs may cause a lot of changes in the operational situation. It has to be ensured that at any operational level requirements must be met and the constraints are satisfied with the presence of DGs controllers. There are few facts to be stated. Conventional control-OLTCs and SC see voltage at the chosen point and take action without considering any impact of the DG. This may result in improper, unnecessary or excessive switching action. Awareness of the impact of DGs in the system may help controllers make effective decisions, whether it is centralized or decentralized.

Volt/Var in a distribution network is addressed in literature and gives many promising solutions. However past research lack the analysis on the impact of DGs on the number of switching of Volt/Var control devices. In literature taking care of coordination among network devices improves profiles, but lacks in switching constraints during the whole period. Utilities do not allow the switching of OLTC or SC in a continuous manner. This binding has to be addressed to generate more realistic operations. Control can either be centralized or distributed with proper assurance of not violating switching regulations practiced by the utility providers.

Chapter 3

Fuzzy Based Method for Volt/Var Control for Optimal Dispatch of OLTC

3.1 Fuzzy Based System

Fuzzy refers to something that is blurry, not to the point or specific or rigid. From the dictionary we find it defined as "not clear". However, in technical language, Fuzzy logic is mostly used in nonlinear systems due to its capability to make human like reasoning. In other words fuzzy logic is a rule-based system or logic-based system. Relying on human experience, fuzzy logic can be used to design a system based on if-else rules. It can have several inputs and outputs.

3.2 Reasoning behind Choosing Fuzzy

Conventional mathematical model is used to solve a real life problem. In reality there are few uses of language-based solving techniques. Natural language has higher potential due to its excellent ability to transfer information. If we think of making a computer which can solve a very complicated problem we can think to give the computer the ability to think like a human. It means infusing the human thought process inside the computer. The most efficient way will be to first model the human thought process since it is capable of mimicking natural language. In view of this, fuzzy logic appears to be a strong tool to achieve that.

In real life most of the problems we encounter are non-linear. Sometimes it is desired by the system to take some approximation to reach the final output. If the model is simple enough mathematical equations to describe the problem will be adequate to arrive at a solution. For complex systems without adequate input arguments, a better way to deal with them is to use fuzzy logic, which is based on many small but acceptable approximations leading towards the solution. Whenever insufficient and inaccurate data have to be processed fuzzy logic becomes handy as it uses linguistic variables.

3.3 Previous work on Volt/Var Control using Fuzzy

Fuzzy logic has been used in previous power system problems enormously. Authors of [93] developed models, methods and control system to increase efficiency of coordinated online control of voltage and reactive power. This method integrates traditional numerical techniques with fuzzy logic technology.A dynamic reactive power boundary voltage and reactive power control method is demonstrated in [83]. Shunt capacitors are not considered in this method. In [84] a new fuzzy control logic based dynamic reactive power boundary substation voltage and reactive power integrated control method is proposed. This method reduces the adjust times of transformer and capacitors effectively. Authors in [85] finds the combination of main OLTC and SC on/off switching operation so that their coordination minimizes the voltage deviation at secondary bus voltage. Fuzzy based reactive power control is used here. In [86] fuzzy logic is used for var resources in a power system for example: OLTC and solar DG bus voltage. This method can handle abnormal or contingency operation to maintain the voltage at all buses within acceptable limits, while minimizes the number of control actions. Authors in [87] presents hierarchical voltage-reactive power control method. It uses fuzzy logic and genetic algorithm for its robustness. This method utilizes the concept of using mutual node voltage influence indices considering it is better approach to use nodal impedance matrix elements. An approach to minimize the voltage deviation using fuzzy set theory is shown in [88] for reactive power control. Load buses voltage; which are considered predetermined are using the sensitive switchable var compensators, OLTC and generator excitations. [89] Presents a fuzzy logic supervision of DGs. This method controls the reactive power injected in the system. [90] describes intelligent volt /var control using fuzzy logic. It is a secondary control system which activates coordination of voltage control among the main and local power systems. Proposed method in [91] handles the disadvantage of traditional voltage control method and the imperfect fuzzy rules gathered based on experience and historical data. This method is able to reduce the number of regulating on-load tap changers and shunt capacitors operations in the system. In [92] an approach to improve the efficiency of coordinated on-line control of Volt/Var control on experimental design is applied to construct diverse types of sensitivity indices, which serve for evaluating efficiency of control actions and, therefore, for constructing fuzzy production rules included in the knowledge base. Authors of [94] considered voltage stability while volt/var control using a fuzzy logic controlled particle swarm optimization. In [95] proper capacitors on/off status and suitable OLTC positions for the 24 hours in the next day is proposed. However DGs are not considered in this paper. [96] demonstrates use of fuzzy logic for voltage control by getting feedback from pilot node uses the voltage of the pilot node as a feedback signal and adjusts voltage level of the pilot node. Generators' reactive power get factorized to coordinate among the participating members. A tabu search algorithm is presented in [97] for optimization of reactive power disptach. This paper satisfies the two objectives including the minimum active power loss and the maximum margin index. A single objective function is achieved from two objectives functions. Final optimal solution is achieved for reactive power dispatch from solution corresponding the maximum of single objective. All these research work mentioned, are either missing the impact of switching operation constraints for OLTC and SC or missing DGs to coordinate along with OLTC and SCs. Proposed method in this chapter finds the impact of DGs on OLTC operation and proves coordination can help to reduce excessive wear and tear of OLTC.

3.4 Proposed Fuzzy Multi Agent based system for voltage and reactive (Volt/Var) power Control

The use of a multi-agent based system is an addition to power systems operations. It is hard for a central regulator to operate without information from different agents of the system as the DGs are variable and cause bidirectional power flow. Even if information is available from the whole network it will still be very time consuming to set the tap of the transformer or switch capacitors after calculation. Another fact is that the exact measured data from each bus is not required as voltage has to be kept inside a dead band. This is actually a safe range of voltage for steady operation. Therefore a fuzzy based Volt/Var regulation technique may relieve the

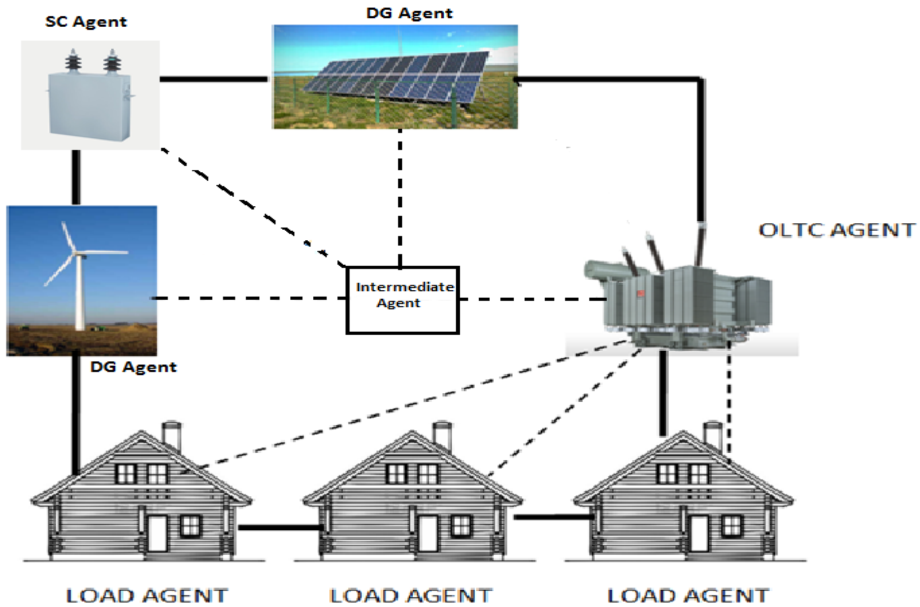


Figure 3-1 Member of Fuzzy Agents

system of complex time consuming calculation. A fuzzy based voltage regulation mechanism for multi-agent control may be the solution to this problem. Figure 3-1 illustrated the member agents for the proposed control. A decentralized control is established to avoid computational time increment. Agents are also clustered into groups so that one from the group can send information to the intermediate agent. A central agent for each group will communicate with each other to reduce complexity in the system. DG will contribute in regulation if it is required to reduce the number of tap changing of the LTC transformer and the switching of capacitors. The fuzzy logic based controller can simply yet accurately deal with the uncertainties in the system through a number of if-then rules. As a result it eliminates the need for a mathematical model of the system which is especially useful for tackling the complexities. Fig.3-2 shows the structure of the proposed fuzzy multi-agent control scheme. The fuzzy controller consists of four principal components: a fuzzification interface, a rule base, inference logic, and a defuzzification interface.

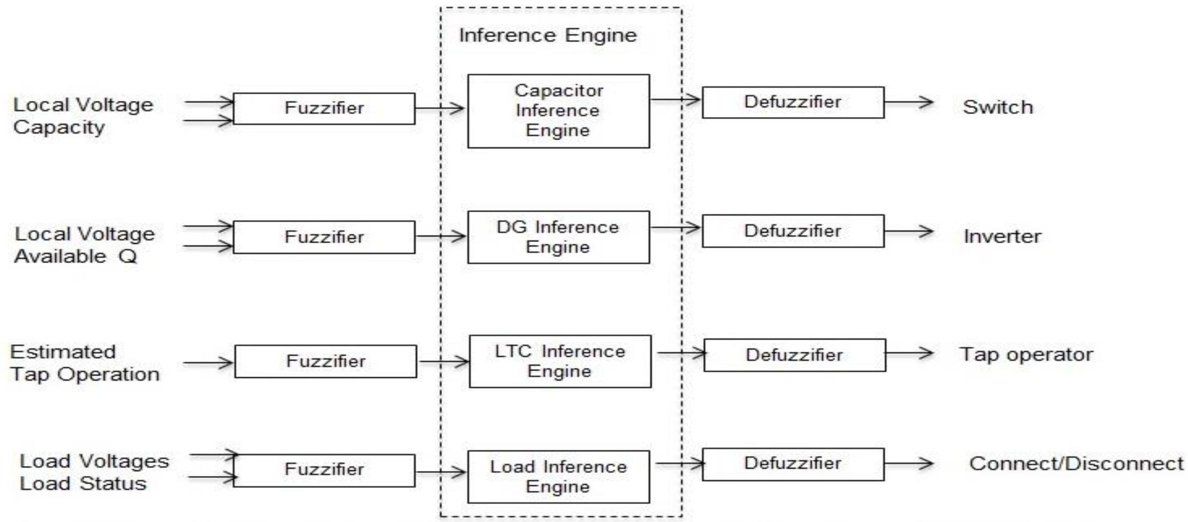


Figure 3-2 Structure of the Fuzzy Decision Maker and agents

3.5 Detailed operation of controller

The fuzzy controller consists of four major components: a fuzzification interface, a rule base, inference logic, and a defuzzification interface. The inputs of the fuzzification block include: secondary side voltage of the LTC transformer, voltage deviation from different DG agents and load agents. The task of a fuzzification interface is to transform the numerical inputs into fuzzy variables. The opposite tis done by the defuzzification interface which transforms the fuzzy variables into the numerical output. Membership functions help to operate the transformations. If –then rules are designed based on experience and historical data or the way designer wants it to perform. Decision is made based on the rules defined prior to the operation. The output from each rule in the rule base is deduced by the inference logic to arrive at a value for each output membership function.

3.5.1 Membership Functions

The fuzzification is done looking at the membership functions and the number of fuzzy signals. The input parameters is fuzzified into corresponding fuzzy signals with five linguistic variables, respectively for the *voltage deviation, address, tap, and reply*. Furthermore, the output parameter is also fuzzified into four linguistic variables.

Membership functions can be triangular and trapezoidal membership functions. It depends on the characteristics of the variables. Examples of membership functions are illustrated in Figures3-3 to Figure3-5.

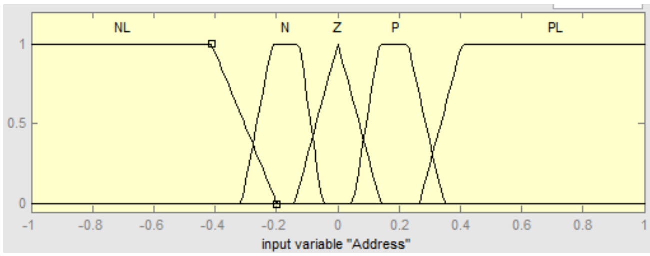


Figure 3-3 Membership function of the voltage violation

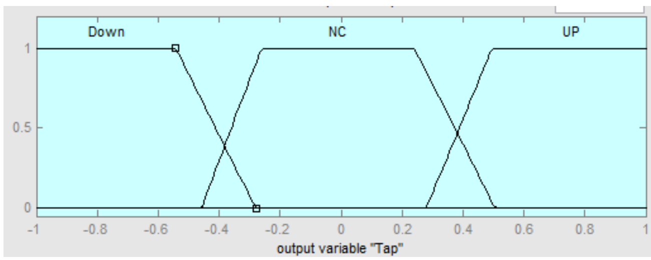


Figure 3-4 Membership function of tap operation

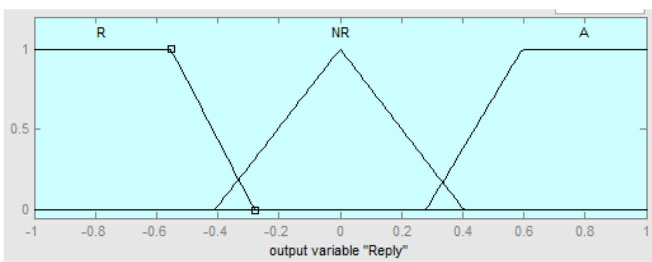


Figure 3-5 Membership function of Reply

3.5.2 Rule Base

Based on the defined fuzzy variables, linguistic rules in the form of if-then are developed to represent the fuzzy decision action process to regulate the voltage of the distribution network. Rule for the agents are explained in detail in section 3.5

3.5.3 Inference

The *Mamdani*-type fuzzy inference method with Max-Min operation fuzzy combination law is used. Several composition methods were introduced in the literature but the commonly used one is the Max-Min operator. Min operator is used to determine the output of each rule while Max operator is used to determine the combined fuzzy output.

3.5.4 Fuzzification and Defuzzification

The fuzzification interface transforms the numerical inputs into fuzzy variables. Oppositely the defuzzification interface transforms the fuzzy variables into the numerical output. This transformation happens considering the membership function. The output from each rule after looking at the member ship function, the inference logic unit converts the output membership function into a crisp value. The value as number is obtained after fuzzy-centroid is utilized for output membership function. Equation (13) is used to generate output:

$$C' = \frac{\sum_{c \in S} c\,\mu(c)}{\sum_{c \in S} \mu(c)} \tag{13}$$

Here, C’: The fuzzified control action

μ(C): The membership function of the inference

S: The support set

3.6 Member Agents of the system

3.6.1 Load Tap Changer (LTC) Agent

LTC is the first to make any decision based on the information it receives. The LTC agent tries to keep the voltage within limit and tries to minimize the number of tap operations to increase the longevity of the transformer. This also avoids excessive wear and tear which causes aging. The fuzzy value of LTC agent receives voltage deviation from all the load agents, calculates its own switching number and receives request from the intermediate agent. Based on the most critical case it makes tap changing action and responds to the request from the intermediate agent. Table 1 shows the output and input behaviors of OLTC agents. Voltage deviations from load buses can be NL (Negative large), N (Negative), Z (No Deviation), P (Positive), PL (Positive Large). Permission message from intermediate agent can be NL (negative large), N (negative), Z (No Deviation), P (Positive), PL (Positive Large). Output to the tap operator can be Up (U), Down (D) or No Change (NC). Reply to the intermediate agent can be Accept (A), Reject(R) or No Reply (N). If an OLTC agent receives a permission message from the intermediate agent it makes a decision based on how many taps occurred until that request arrived. If tap operation is considerably low it rejects the permission request. Otherwise with the high tap operation it accepts, DG or SC is capable of contributing.

3.6.2 Distributed generator (DG) Agent

DG agents can change their active and reactive power generation based on the information it receives. DG agents always try to keep its own bus voltage to the standard level to maximize generation and get optimal revenue. In this paper we assumed that DG agents will send the intermediate agent their voltage deviation from the grid line to contribute to regulating grid voltage. If the intermediate agents accept its request; it will start to regulate the Volt/Var by its own. Table 2 shows the output and input behaviors of LTC agents. Voltage deviations from DG buses can be NL (Negative large), N (Negative), Z (No Deviation), P (Positive), PL (Positive Large). Permission message sent to the

Tap Operation					
Permission\ Voltage Deviation	NL	N	Z	P	PL
NL	D	D	NC	NC	U
N	D	D	NC	NC	U
Z	D	NC	NC	NC	U
P	D	NC	NC	U	U
PL	D	NC	NC	U	U
Reply to Intermediate Agent					
Permission\ Voltage Deviation	NL	N	Z	P	PL
NL	R	R	A	A	A
N	R	R	A	A	A
Z	N	N	N	N	N
P	A	A	R	R	R
PL	A	A	R	R	R

Table 1 Rules for LTC agents

Permission sent to intermediate agent					
Reply\Voltage Deviation	**NL**	**N**	**Z**	**P**	**PL**
A	Z	Z	Z	Z	Z
R	Z	Z	Z	Z	Z
NR	NL	N	Z	P	PL
Real Power generation when DG agent has no capacity to control Volt/Var					
Reply\Voltage Deviation	**NL**	**N**	**Z**	**P**	**PL**
A	M	M	M	M	M
R	D	D	M	I	I
NR	M	M	M	M	M
Reactive Power Injection when DG Agent has capacity to control reactive power					
Reply\Voltage Deviation	**NL**	**N**	**Z**	**P**	**PL**
A	M	M	M	M	M
R	I	I	M	D	D
NR	M	M	M	M	M

Table 2 Rules for DG agents

intermediate agent can be NL (negative large), N (negative), Z (No Deviation), P (Positive), PL (Positive Large). Reply from the intermediate agent can be Accept (A), Reject(R) or No Reply (N).

Based on the reactive power (Var) control capacity of the DG output to control for real power and reactive power generated by the DGs can be Increase (I), Decrease (D) or Maintain (M).

3.6.3 Switching Shunt Capacitor (SC) Agent

One switching SC bank is placed at the substation bus. It sends its capacity to the intermediate agent and waits for a reply. After getting a reply from the intermediate agent it makes the switching action. The permission it sends to the intermediate agent can be Very High (VH), High (H), Medium (M), Low (L), No capacity (Z). Table.3 shows the switching operation of SC. If the intermediate agent accepts the permission sent, the SC agent will take action using the rules mentioned in table 3.

3.6.4 Load Agents

Load agents do not directly take part in voltage regulation. It measures the bus voltage where it is connected. It compares the measured voltage with the nominal voltage and then sends the difference to the LTC agent. Voltage deviations from load buses can be NL (negative large), N (negative), Z (No Deviation), P (Positive), PL (Positive Large).

Switching of Shunt Capacitor after getting reply from Intermediate Agent

Capacity/Voltage Deviation	NL	N	Z	P	PL
VH	VH	H	VH	L	Z
M	VH	H	M	L	Z
L	VH	H	L	L	Z
H	VH	H	H	L	Z
Z	VH	H	Z	L	Z

Table 3 Rules for SC agents

3.6.5 Intermediate Agent

The intermediate agent is the coordinator between the OLTC and the other control agents (DG agent and SC agent). First it gets information on available capacity from the DG and SC agents. Based on

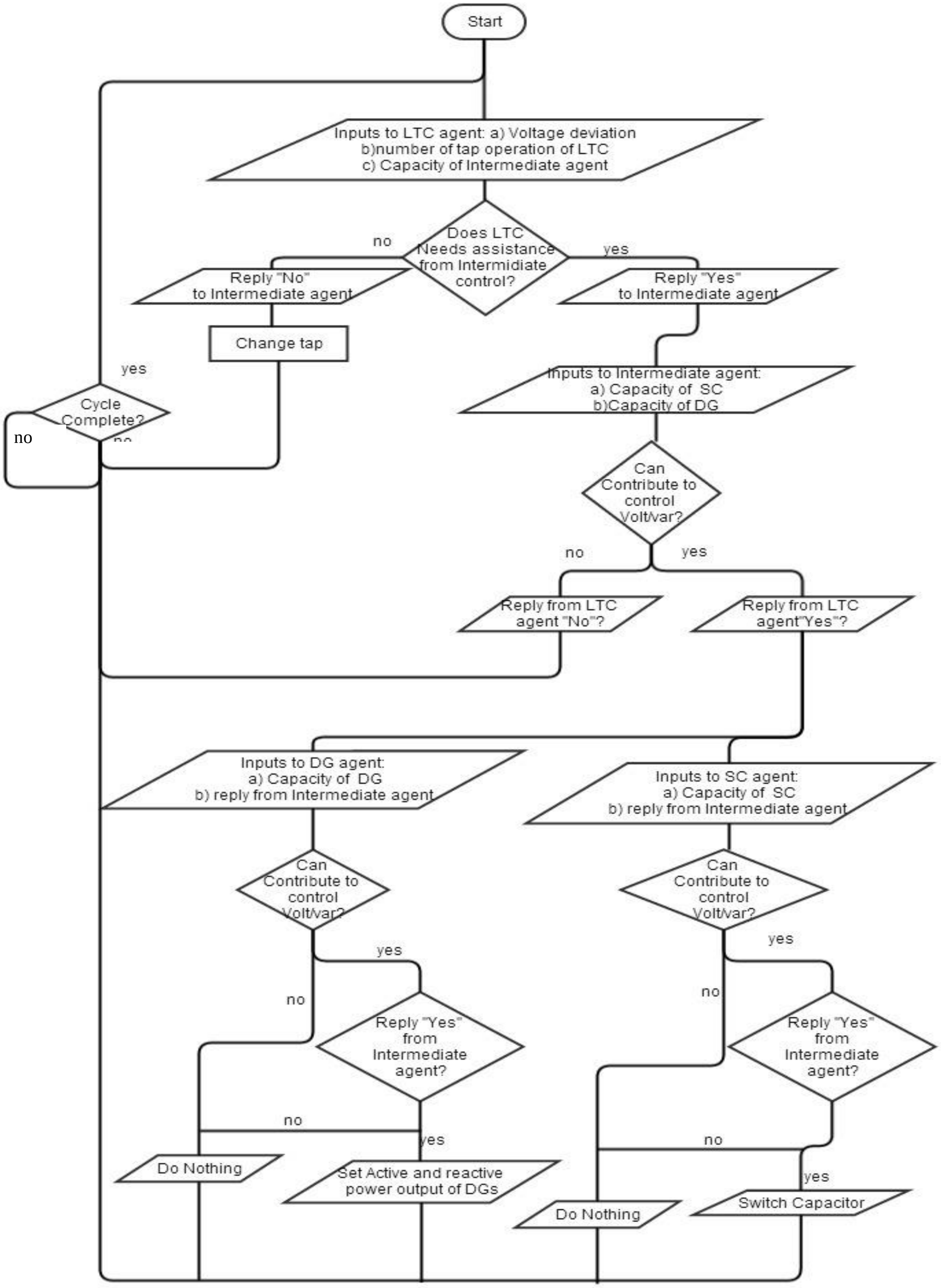


Figure 3-6 ***Flow Chart for Co-ordination among agents***

that, it approaches the LTC agent to seek permission to control Volt/Var via the DG or SC agent. If permission is accepted by the LTC agent based on the number of switching of the capacitor and the reactive power available from DGs, the intermediate agent accepts permission from DG and SC agents.

3.7 Coordination among agents

All agents coordinate every ten minutes to set the optimal switching operation for LTC and SC and the generation value for DG. In 24 hours a total of 144 coordination processes take place. Figure 3-6 shows the flow chart for each process.

3.8 Simulation Results

An 8 bus distribution system is used to simulate the proposed control mechanism. Figure 3-7 shows the test system. In bus numbers 6 and 8 two DGs are connected. One SC bank is connected at bus 3. DG has to generate the maximum power that it is capable of. However, during the off peak hours

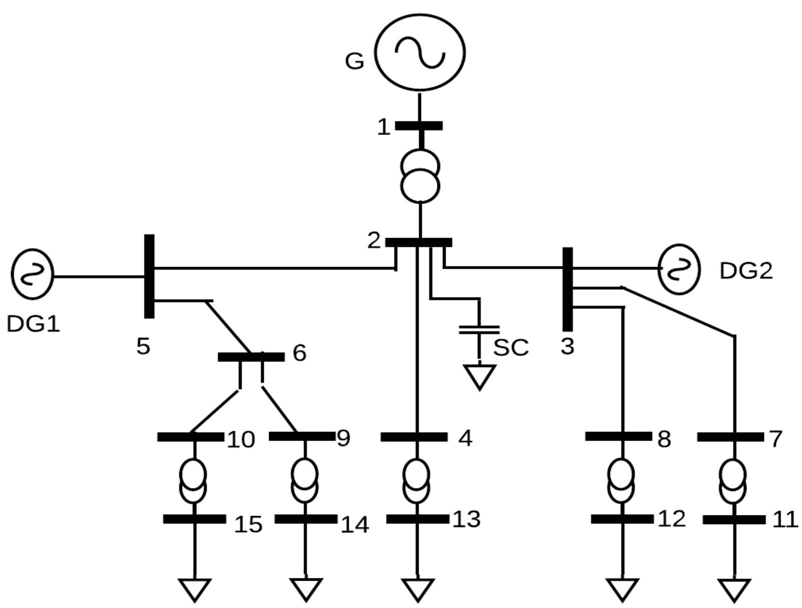


Figure 3-7 ***8 bus test distribution system***

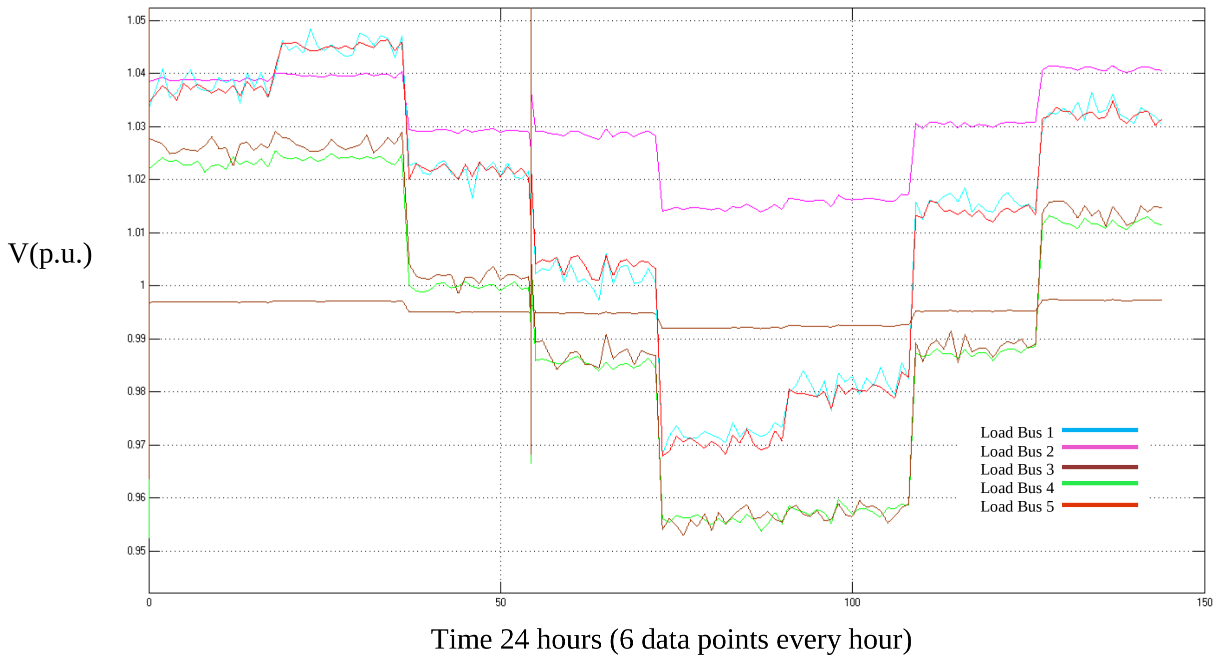


Figure 3-6 Voltage at Load buses after coordination

loads are limited. DGs have to curtail their active power to keep the voltage within its specified limit during this time. From Figure 3-8 it is seen that this method can keep the voltage within the acceptable range at the substation. Fuzzy-based controller can reduce the number of tap operation as shown in Figure 3-9. Before coordination among the agents, the number of switching during the whole day totalled to 30. After coordination however, the number was reduced to 16. Although the reduced number is still large it can be modified by putting more constraints in the system.

3.9 Result Summary

Fuzzy logic gives the freedom to implement coordinated but distributed control. As found in literature it is clear that DGs have effects on the number of operations of the OLTC. This has been verified by the 8 bus distribution network to observe how DGs affect the total number of switching during the whole day. Control action has been taken every 10 minutes of each hour totaling to 144 times a day. Without any coordination the single OLTC in the network is found to operate more than 30 times a day which is not acceptable to the utilities. The proposed fuzzy multi-agent based method introduces coordination among the agents/members. After simulation it has been verified that the number of switching can be reduced without causing any voltage violation.

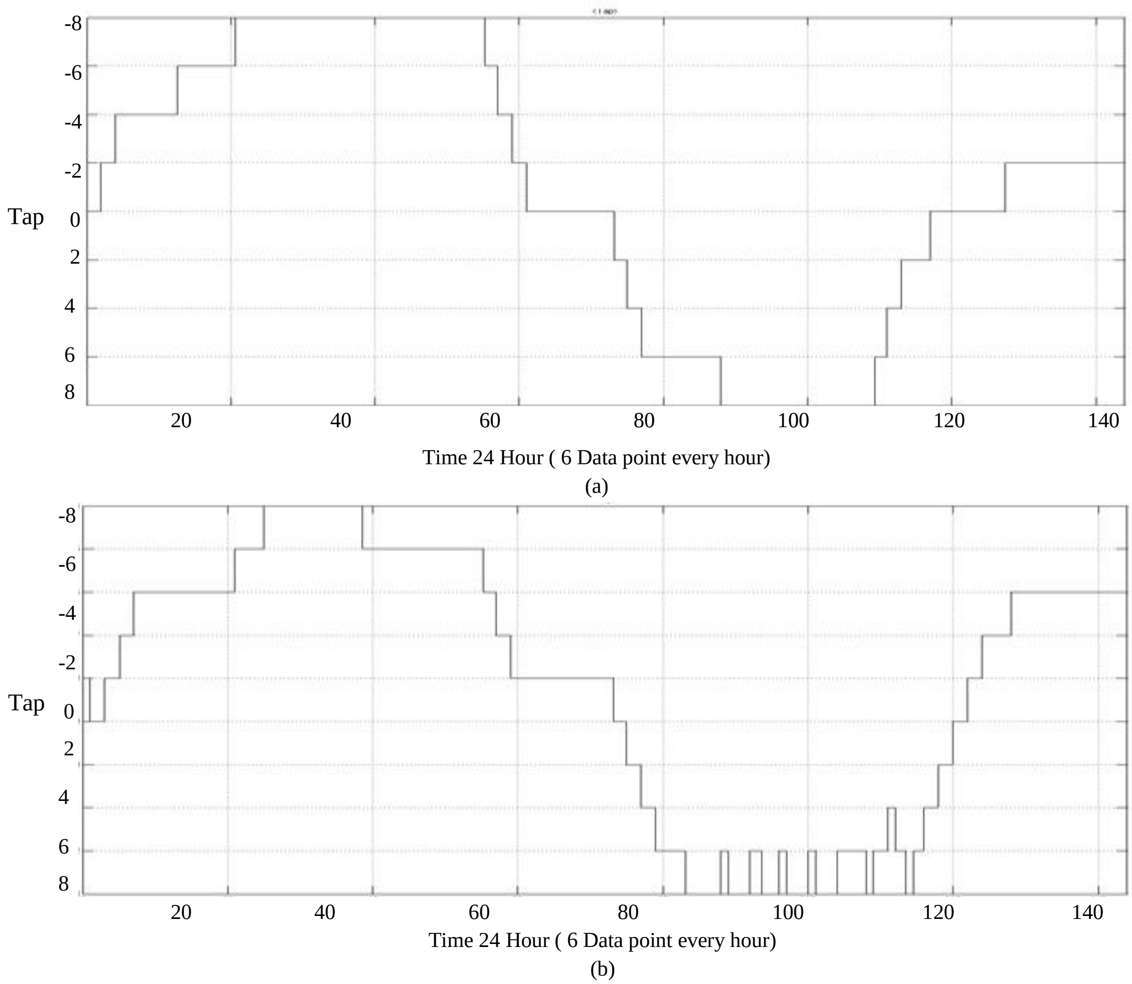


Figure 3-7 Number of OLTC operation (a) with coordination (b) without coordination

Considering that the number of operations of the OLTC is still high, a better method has been proposed in chapter 4. The problem has been dealt with heuristic-based method in the following chapter.

Chapter 4

Genetic Algorithm Based Volt/Var control for Optimal Dispatch of OLTC and SC in the Presence of DG

4.1 Research on Volt/Var Control using Genetic Algorithm

The problem of Volt/Var control and optimization is a very important aspect for optimal operation of power systems. In order to obtain proper voltage regulation, minimum active power losses and optimal reactive power dispatch many methods have been tried out by the researchers. In recent years intelligence based technique like Genetic algorithm is proposed in many papers to solve power systems problems. Few researchers dealt Var control problem separately. Authors of [98] proposed genetic algorithms (GA) for the optimal reactive power dispatch problem. In this method a few subsystems are generated from the main system. Interbreeding is adopted among the subsystems to find the solutions. However this method has higher complexity when it comes to computation. All control variables are converted discrete ones by replacing them as integer values. By doing so accuracy might be less generating invalid outputs. In paper [99] presented investment planning problem where a simple GA with successive linear programming method for the reactive power dispatch is used. [100] uses hybrid GA-interior point method to optimally dispatch reactive power and is very complex as the computational burden increases a lot. Recently, Authors of [101] shows self-adaptive real coded genetic algorithm for optimization of reactive power dispatch. [102] proposed a method for reactive power dispatch using general quantum genetic algorithm. [103] shows optimization to minimize active power losses while maintaining the quality of voltages using GA. In [105] the GA is compared with an integer programming-based solution method for optimal volt/var control by maintaining bus voltage and generator reactive power in a power system. This method is better because of lower computational time. [106] presents a method to regulate the voltage profile in the distribution system using wind DG, static compensator and OLTC. Genetic algorithm helps to reduce MW loss in the system .The operational constraints are fulfilled in this method. In [107] it displays and fulfills the goal intended for reactive power optimization control, by minimizing loss and invest cost minimization using GA. [108] presents a method in which it is ensured that every candidate bus in every section and OLTC, voltage regulator will be operated using GA for optimum reactive power. This method assumes reactive power control devices are generators, tap positions of OLTC transformers but misses shunt capacitors. The validation of this work is done by testing its on a practical grid. [109] presents a new approach of volt/var control having objectives if minimization of generation cost, the minimization of real power losses flowing in a power system. Voltage profile improvement is observed in this method. Through previous research work it is seen that GA has been vastly used for active loss minimization, voltage control by operating DGs, cost minimization, reactive power dispatch. There are few papers which are highly focused on the switching constraints of OLTC and SC. In this chapter a method of optimizing Volt/Var control using GA keeping the switching number as a constraint is proposed.

4.2 Problem Formulation for Proposed method

In a steady state power system the Volt/Var control problem can be solved using the power flow to find optimal switching for voltage and reactive power controlling devices like OLTC and SC. The proper definition of the problem including its objective function and several nonlinear control constraints is the first step towards the solution. Volt/Var control problem in the radial distribution system can be considered as a nonlinear optimization problem with continuous and discrete variables.

In this chapter a Volt/Var control problem in the distribution system with solar DG and wind DG will be studied. Solar DGs will be considered as an active power source with random output. Solar DG and wind DG output data are real historical data. Optimization of a nonlinear problem is considered with an objective function, which is loss calculated over a 24-hour period. The goal is to minimize the MW losses for load profiles for 24 hours. OLTC and SC are held responsible for voltage control. All other voltage control devices are not considered in this study. As constraint function the voltage range is mentioned. Voltages at any bus are not allowed to cross the dead band. Previous studies did not consider the effect on the switching of OLTC and SC while considering the integration of DGs in the network. This thesis focuses mostly on the number of switching for both OLTC and SC as it has tremendous effect on their lifetimes. Moreover, these devices are not allowed to switch above a certain number of operation by the utility industries. No matter how much DGs are injected in the system these voltage control devises must limit their number of operations. This is considered another constraint in the problem. Power flow algorithm is required to estimate the effect of DGs and loads on the network profile. AC Newton Raphson power flow algorithm is used because it is a robust method to run power flow. Real and reactive power demands by the loads are taken for a 24-hour period with an interval of 1 hour. Finally optimal dispatch for OLTC and SC for the 24-hour period for efficient Volt/Var control is formulated below:

Objective function= $min \sum \quad P_{loss}$ (14)

Constraints function:

$V_j^{lb} \leq V_j = \leq V_j^{ub}$ j=1, 2,3,4,5..........., B (15)

$T_j^{lb} \leq T_j = \leq T_j^{ub}$ j=1, 2,3,4,5..........., K (16)

$C_j^{lb} \leq C_j = \leq C_j^{ub}$ j=1, 2,3,4,5..........., S (17)

Equation (14) is the objective function which is set to minimize the power loss. Equations (15)-(17) are the constraint functions set to limit the voltage and tap/switching operations. This problem has continuous and discrete variables.

In voltage constraints equation (15) lowers the limit for the voltage, and is considered V_j^{lb}= 0.95 p.u. as standard and upper limit for voltage is considered V_j^{ub}=1.05 p.u. For the number of tap change constraints equation (16) lowers the limit for this and is considered T_j^{lb}= 0 and upper limit is considered T_j^{ub}=12. For the number of shunt capacitor switching constraints, equation (17) lowers the limit and is considered S_j^{lb}= 0 and upper limit is considered S_j^{ub}=7.

Our objective function is dependent on load and DG profile and power capacity constraints. Corresponding equations are given below.

$$P_{fb} - P_{tb=}V_{fb}\sum_{j=1}^{N} V_{tb}[G_{ft}\cos(\delta_f - \delta_t) + B_{ft}sin(\delta_f - \delta_t)] \quad (18)$$

$$Q_{fb} - Q_{tb=} - V_{fb}\sum_{j=1}^{N} V_{tb}[G_{ft}\sin(\delta_f - \delta_t) + B_{ft}cos(\delta_f - \delta_t)] \quad (19)$$

Any type of DG has the following criterion for power generation and voltage boundary.

$$P_G^{min} \le P_G < +P_G^{max} \quad (20)$$

$$Q_G^{min} \le Q_G < +Q_G^{max} \quad (21)$$

$$V_G^{min} \le V_G < +V_G^{max} \quad (22)$$

4.3 Genetic Algorithm Components and Features

GA optimization runs decoding, fitness evaluation, reproduction, crossover and mutation to generate results. Initial population is generated after the user defines the population size. Chromosomes are identified if the populations are encoded as binary numbers. Length of chromosomes is another important factor of GA. In summary GA has 11 entities on which output depends: 1) initial population; 2) encoding of chromosomes; 3) population size; 4) fitness function; 5)crossover operation and rate; 6) elitism preserving rate; 7) termination criterion; 8) gray code, the better one of the coding methods; 9) mutation operation and rate; 10) parent-selection operation; and 11) length of chromosomes

Reproduction, crossover and mutation are the three most important entities. GA is an encoded process and considers outputs from the power flow which simplifies the objective function and constraints function. Eventually the operation process checks the fitness function and avoids the complexity of heavy mathematical modeling. It does not design a system used for various problems. Initial solution is generated by random function. However, constant fitness checking eventually leads toward the optimum solution. It is not blind search. With the initial settings or by proper tuning of the initial population local optima can be avoided successfully. All these positive attributes of GA make it a very efficient tool for the optimization of our problem.

4.4 Optimization method

OLTC and SC are non-linear voltage regulation devices. Mathematical modeling of such devices ends up being non-linear in nature. OLTC keeps the secondary voltage within limits and SC switches on/off based on the system requirement. Modeling these devices and running optimization becomes harder due to their non-linear properties. With the increment of the number of elements the complexity rises and the time required for computation also increases. To tackle these issues GA optimization technique is a well-known heuristic-based method. However, defining the proper fitness function for the problem is a challenge as fitness function directs the optimization to the optimal solution instead of getting stuck into the local minimum. Among the many solutions generated by GA the best optimization method is through evolution. As found in many heuristic-based techniques in literature GA gives very satisfactory results for power system optimization technique.

As the output of GA-based optimization technique depends on fitness function, the formation of fitness function along with the solution variable representation is discussed in this section. The population generated in GA optimization is a candidate solution for the problems. Population numbers depend on the precision of the output. More precise solutions demand larger numbers of the population. However larger populations tend to take more time to generate solutions. In our particular Volt/Var optimization problem more than one decision variable is involved. For each variable a string of integer number is generated. All integer strings for all variables create a larger string.

4.4.1 Boundary Value Section for Decision Variables

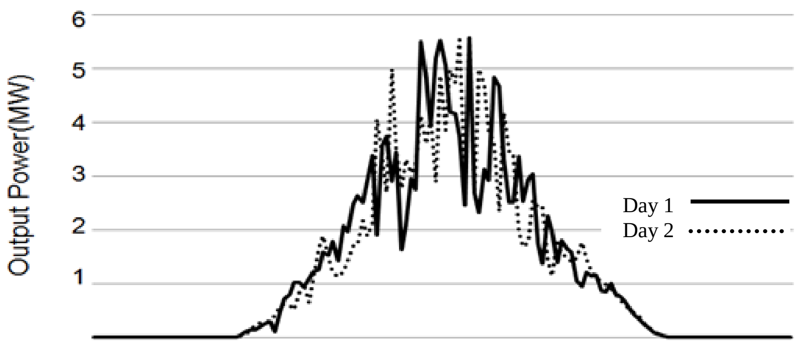
The objective of the problem is to find the optimal dispatch of OLTC and SC for the 24-hour period for the given constraints. The location and size of capacitors are prefixed. The status of each capacitor at any hour has to be determined along with the tap position of the OLTC. The solution to the problem must contain the 24-hour status of each capacitor and OLTC.

We have 6 capacitors in the test system. For each capacitor the solution must contain 24 values representing the 24-hour status. In total 6*24=144 variables for capacitors and 24 variables for OLTC are required as we have only one OLTC in the test system. The summation of 144+24=168 variables is required in the solution. The solution variable will look like a string of 168 integers.

The evaluation of objective function depends on the variables generated by the GA. Fitness value of each individual of the population generated by the GA needs decoding. Variables for capacitor do not need to be decoded as they can only be 0 or 1 representing 'ON' or 'OFF' status of the $tap = 1 \pm 0.125 * T$ capacitor. For the OLTC as a 16 tap transformer, the value generated by the GA can be any integer T between -8 to +8. This integer value is then decoded using the following equation for fitness in the Matlab code for power flow as shown in Appendix B. For each individual of the population Matlab runs the power flow while keeping the constraints within considerations.

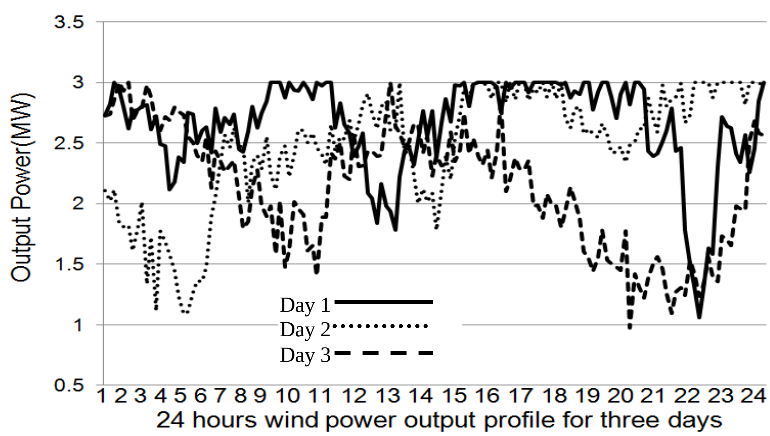
4.4.2 Determine network status for every hour

For every hour the load value and DG value are updated before running any power flow or GA optimization. Figure 4-1 shows the 24-hourly load and DG profile. Data for load profile is given in Appendix A. The 30-bus test system we have studied is shown in figure 4-2 .For every hour's load, the DG profiles are different. A power flow program is used to get the bus voltages. With the voltage profile generated for each hour GA optimization can determine which profile represents less voltage violation and reduced power loss status.

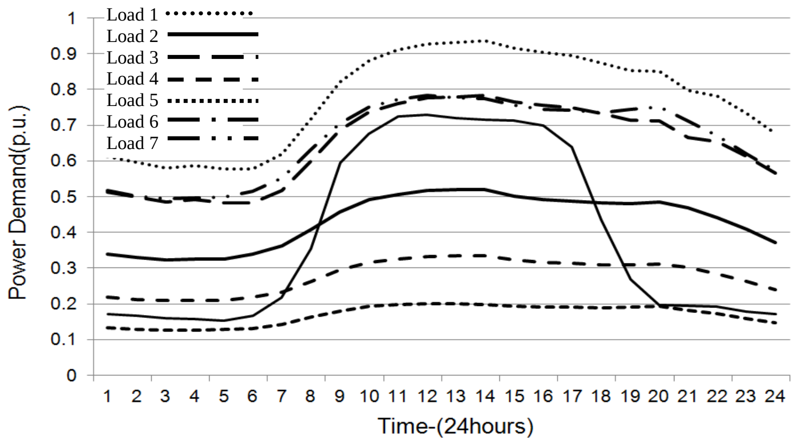


Time-24 hours (144 data points)

Solar DG output profile for two days



(b)



(c)

Figure 4-1 (a) Solar type DG Output Power (b)Wind type DG Output Power (c) Typical load profile

4.4.3 Fitness function selection

Matlab has high efficiency in processing large amounts of data. Genetic Algorithm and the Direct Search Toolbox (GADS) helped to solve this problem to a great deal as it is hard to mathematically model this problem. GADS is a good approach to use if the objective function is discontinuous or highly nonlinear, is random or non-differentiable. Considering the objective function is non linear, GA function command lines are used to solve the problem. Objective function is written before using GA which will then attempt to find the minimum value of the objective function for optimization. This is the aim of the fitness function. Fitness function is coded like Appendix B.

4.4.4 Constraint Function selection

Constraints function is shown in Appendix B. It has nonlinear constraints addressing the voltage violation. Maximum and minimum voltage at any bus at any hour can be a maximum of 1.05 and can be a minimum of 0.95. Maximum operation for the capacitor is chosen at 7 here for a single day. Maximum operation for the OLTC is chosen at 12 for a single day. The lower and upper limit for the status of the capacitor can be either 0 or 1.The lower and upper limit for OLTC tap setting is between 0.9 - 1.0.

4.4.5 Options settings for GA

To avoid getting local minima and to increase the diversity of generation setting the initial range for the first population is needed. Tap position initial range is set to [-4,0]. It does not need to be the best value. However, this process helps to generate the population near the best individual.

Population size is another important factor. Bigger population sizes ensure accurate solutions. We chose our population size to be 300. It helps to avoid local minima but increases calculation time. Elite count in this case is at 20 to keep it under reproduction. Tournament approach is selected for the selection function. Setting the generation to 600 gives the GA adequate time to converge to a solution before termination. We kept the stall generation to 400. Genetic algorithm will stop running if the objective function value is less than the function tolerance selected.

4.5 Controller Architecture

Based on all given parameters and constraints and objective function described, the flowchart below describes how the controller performs its task. The controller is implemented as a Matlab program. A flowchart of the controller algorithm is shown in Figure 4-2 after the power flow ran for the 24-hour period and completed the necessary calculation and is ready with the data. Newton Raphson method has been used since our test system is large enough to generate multiple equations during the 24 hours load flow. Before sending input argument to the GA optimizer, Newton-Raphson Load Flow will run every hour of the day to generate all possible voltage and loss profile. To optimize the voltage profile the GA must evaluate the objective function. This function is a mathematical representation of the loss profile for the 24-hour period of the test network. The input argument to evaluate the objective function is the summation of all the per-unit voltage level of all 30 buses in the test network. All the Matlab file to run the power flow is given in Appendix B.Power flow runs based on all the data such as network topology, line impedances and bus types. After getting the data running load flow, the genetic algorithm optimizer runs. The controller generates various tap positions of OLTCs and switching for the SC. For every population generated the voltage is calculated at all buses, including those at generators or reactive power sources. Thus the variables that the GA will adjust are the tap settings of OLTCs and the switching of the SC to satisfy the objective function. We can also describe the control mechanism by the following steps:

- Input from radial network

  a) real and reactive power demand for all loads at every hour of the day

  b) radial distribution network structure

  c) location of OLTC

  d) location of shunt capacitors

  e) line parameters

  f) location and type of DGs

  g) penetration level of DGs

  h) population size

  i) stopping criteria

  j) variable boundaries

  k) Initial population generation based on Genetic algorithm optimization parameters

  l) Calculate fitness value for every generation of the population

  m) Tournament selection, crossover and mutation execution to generate new population

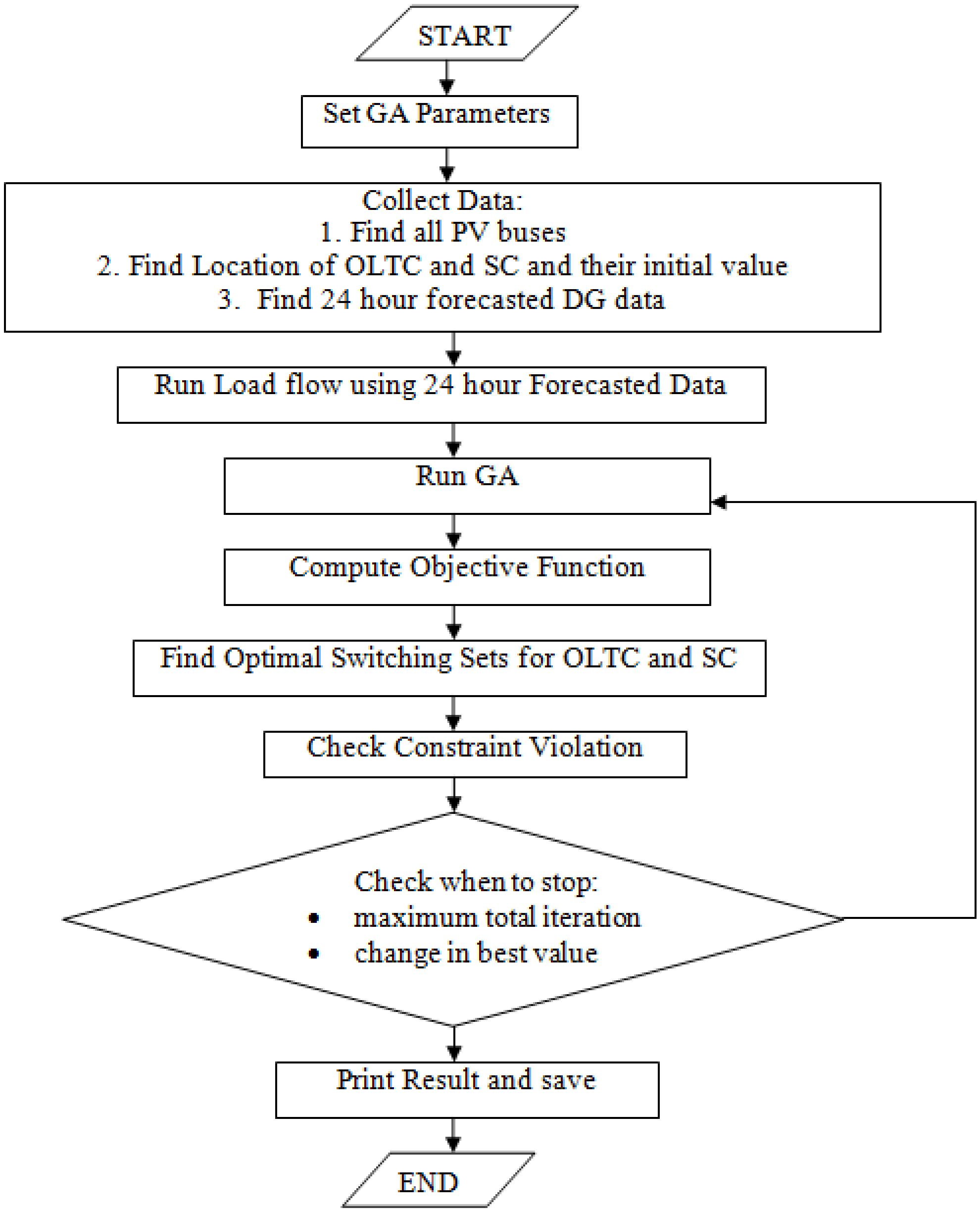


Figure 4-2 Flow Chart for GA optimizer

a) For new set of population check the objective function and fitness function.

- Genetic algorithm optimization parameters

    a) encoding unknowns

b) number of variables

- If violation occurs, iteration number increases.
- For every iteration if fitness value is better than previous values preserve it with the population otherwise keep the previous
- Keep on iterations until stopping criterion is satisfied
- Display the tap and switching order for 24 hour period for the OLTC and SC respectively

4.6 Simulation and Verification

4.6.1 Test System: 30 Bus Distribution network

The 30-bus radial distribution network is illustrated in figure 4-3. It has a conventional generator at bus 1 and it is also considered as a slack bus. There are 7 capacitors is our network. Capacitor location and size are kept as listed in [41]. Two solar DGs are connected at buses 15 and 18. Four

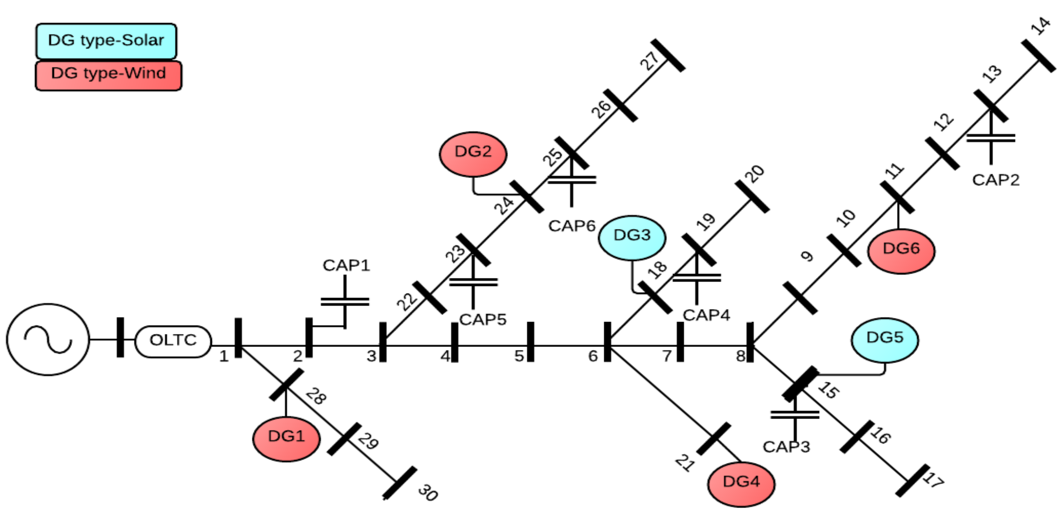


Figure 4-3 30 Bus test system

wind DGs are connected at buses 11, 21, 24, 28. Maximum load demand of the system is kept at 6 MW and maximum reactive power demand is kept at 3 MW. As there are six DGs in our system the total penetration level is kept at 40% of the total load demand. The 30-bus system has 1 generator, 6 shunt capacitors and 22 loads. The shunt capacitors are located at buses 1, 19,13,23,25. This network is found widely in literature for testing and simulation purposes.

4.6.2 Test Case 1: Test System without LTC, SC and DG

At the beginning there is no SC, OLTC and DG in the system. Voltage at all the buses is shown in figure 4-4 and few other properties are recorded as below:

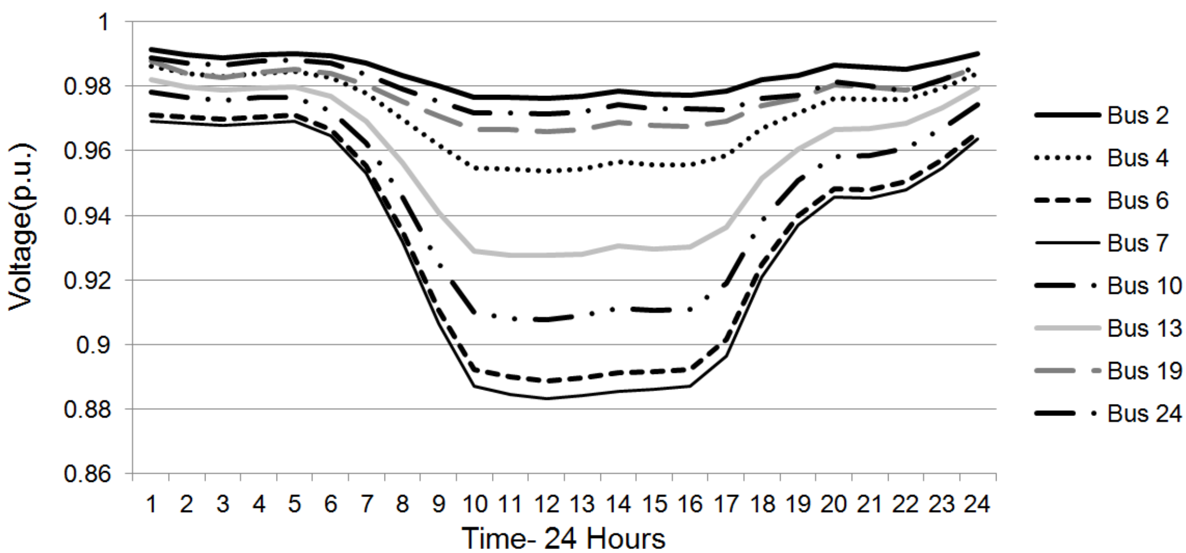


Figure 4-4 Voltage at all buses for 24 hour period for test case 1

- Minimum loss at any hour = 0.0706
- Minimum Voltage = 0.8645 p.u
- Maximum Voltage = 0.9908 p.u
- Total loss during the day = 6.4290 MW

- Maximum loss at any hour = 0.5641 MW
- Minimum loss at any hour = 0.0706 MW

4.6.3 Test Case 2: Test System with Shunt Capacitors

In this test case, the shunt capacitor is added in the system and programmed to operate in voltage control mode, which is one of the rational technique followed by the utilities to operate shunt capacitors. The DGs are added to the system to verify the effect of DGs on the number of switching. Simulation for over a month period is shown in Figure 4-5. The X axis represents the capacitor number and the Y axis represents the total number of switching during a month. This figure signifies that the presence of DG can increase the number of switching thus decreases the lifetime of the capacitors.

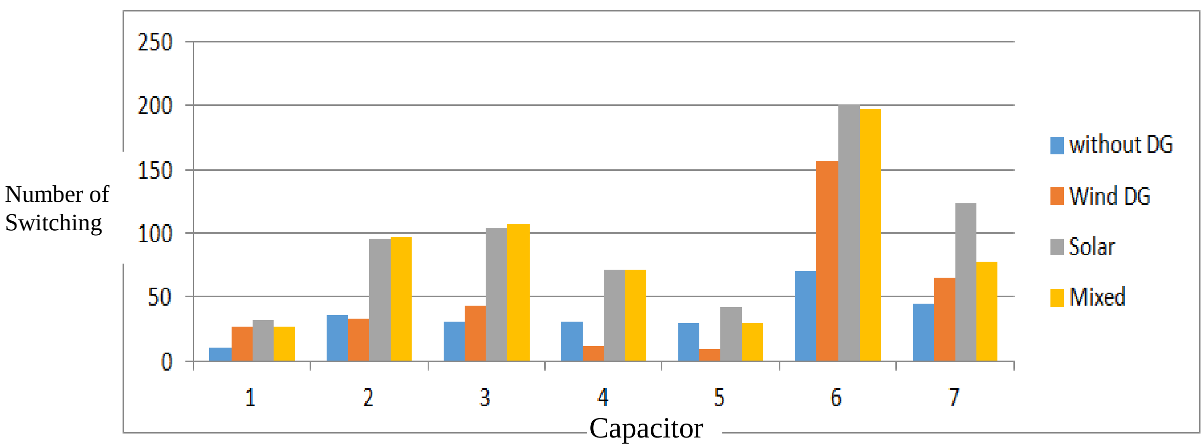


Figure 4-5 Effect of DGs on Shunt Capacitor Switching for 31 days

4.6.4 Test Case 3: Voltage Control with, OLTC, DG and Shunt Capacitors (DAY-AHEAD)

Our proposed GA based Volt/Var control technique is applied here. The following results are obtained. From Figure 4-2 and Figure 4-4 we can see the drastic difference in voltage profile using with control and without control. From Table 4-1 it is clear that the operation of OLTC and SC for the 24-hour period obtained from the proposed method is satisfying the constraints.

Our proposed method has generated results based on the forecasted DG data. When compared with the voltage and loss profile generated from the actual DG data, we get Figure 4-6 and Figure 4-7. From the figures it is visible that forecasted data are adequate for the proposed method. However, the loss is higher than the actual DG data that is shown in Table 4-2.

Hour	cap1	cap2	cap3	cap4	cap5	cap6	OLTC
1	1	0	1	1	0	1	-2
2	1	0	1	1	0	1	2
3	1	0	1	1	0	1	0
4	1	0	1	1	1	1	0
5	1	1	1	0	1	1	0
6	1	0	1	1	1	1	0
7	1	0	1	1	1	1	-4
8	0	0	1	1	1	1	-4
9	1	0	1	1	1	1	-4
10	1	1	1	1	1	1	-3
11	0	1	1	1	1	0	-3
12	0	1	1	1	0	1	-2
13	0	1	1	1	0	0	-2
14	0	1	1	1	0	1	-2
15	0	1	1	0	0	1	-2
16	0	1	1	0	1	0	-3
17	0	0	1	0	1	1	-3
18	0	0	1	1	1	1	-3
19	0	0	1	1	0	1	-2
20	1	1	1	0	0	1	-2
21	1	1	1	0	0	1	-2
22	1	1	1	0	1	1	-1
23	1	1	0	0	0	1	-1
24	0	1	0	1	1	0	-1
switching	5	5	1	6	7	7	7

Table 4 Operation of OLTC and SC for 24 hour period obtained from day-ahead control method

Voltage	Day Ahead	Actual
Maximum	1.0496	1.0501
Minimum	0.941	0.94

Table 5 Maximum and Minimum voltage during the whole day

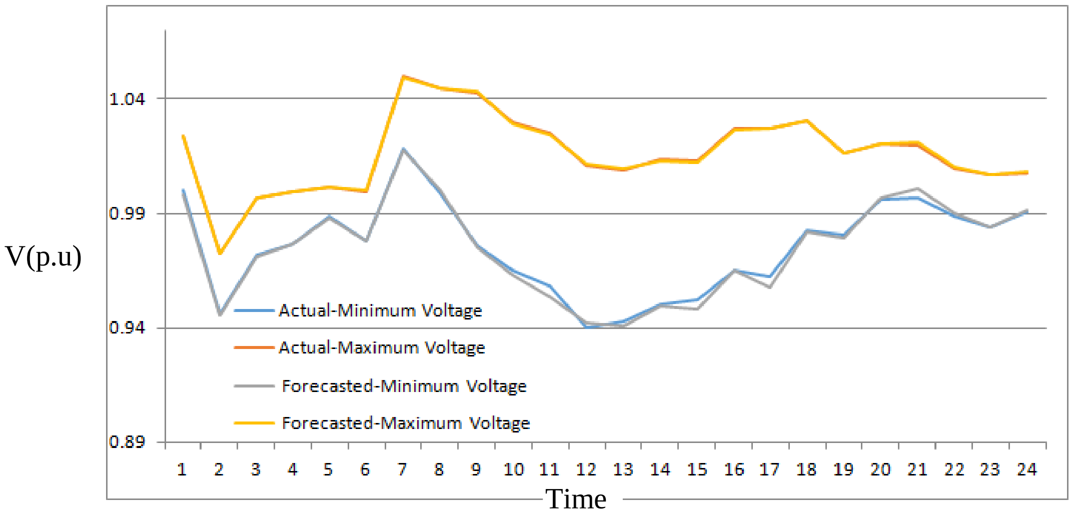


Figure 4-6 Comparison of Voltage profile between actual and day-ahead (24 hour) forecasted solar and wind profile

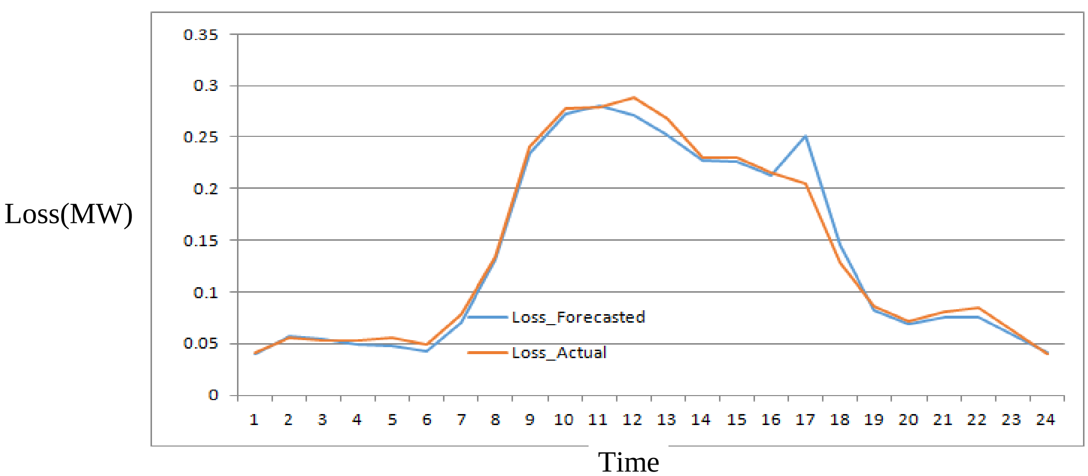


Figure 4-7 Comparison of Loss profile between actual and day-ahead (24 hour) forecasted solar and wind profile

4.6.5 Test Case 4: Voltage Control with, OLTC, DG and Shunt Capacitors (Adaptive)

To improve the loss profile and get better operation for OLCT and SC, adaptive control is tested here instead of using the 24-hour or day-ahead control. In contrast to the day-ahead control, adaptive

Data	Day Ahead	Actual
Total Loss	3.267	3.3036

Table 6 Loss Comparison

Hour	cap1	cap2	cap3	cap4	cap5	cap6	OLTC
1	1	1	1	1	0	1	-3
2	1	1	1	1	1	1	-3
3	0	1	1	1	1	1	-3
4	0	1	1	0	0	1	-4
5	1	0	0	0	0	1	-4
6	0	0	0	0	0	1	-4
7	1	1	0	1	1	0	-4
8	1	1	0	1	1	0	-4
9	1	0	0	0	1	1	-4
10	1	1	1	1	1	1	-4
11	1	1	1	1	0	1	-4
12	1	1	1	0	1	1	-4
13	0	0	1	1	0	0	-5
14	0	0	1	1	0	0	-5
15	1	0	1	1	0	0	-4
16	1	1	0	1	1	1	-4
17	1	1	0	0	1	1	-4
18	1	0	0	0	0	1	-4
19	1	1	1	0	0	1	-4
20	1	1	0	1	0	0	-4
21	1	1	0	1	1	0	-4
22	1	1	0	1	1	0	-4
23	1	1	0	1	0	0	-4
24	1	1	1	1	0	1	-3
switching	6	7	7	8	10	6	4

Table 7 Operation of OLTC and SC for 24 hour period obtained from adaptive control method

Voltage	Adaptive	Day Ahead
Maximum	1.0499	1.0501
Minimum	0.9648	0.94

Table 8Max and Min Voltage Comparison between Adaptive and Day-Ahead Control

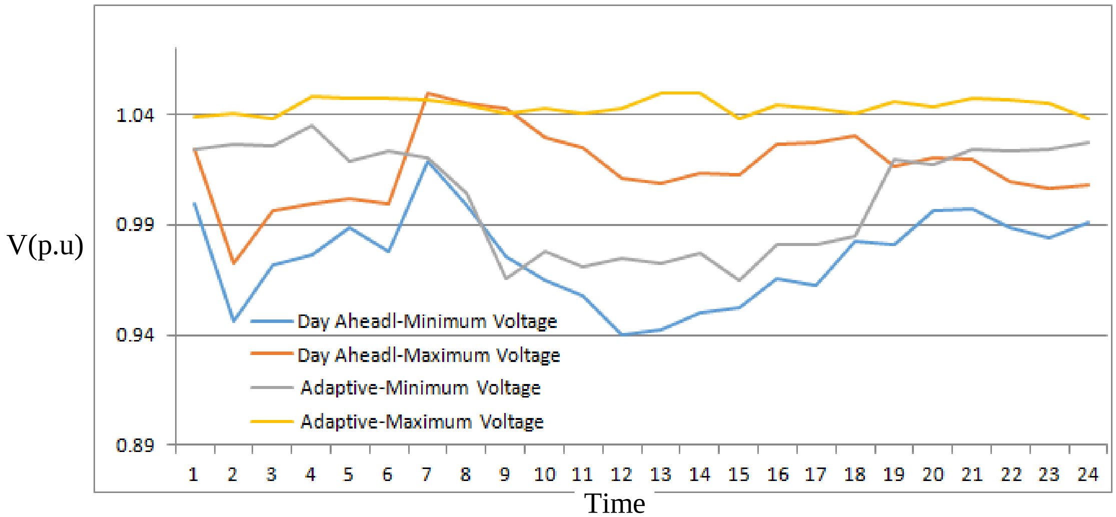


Figure 4-8 Comparison of Voltage profile between Day- ahead and Adaptive (6 hour) forecasted solar and wind profile

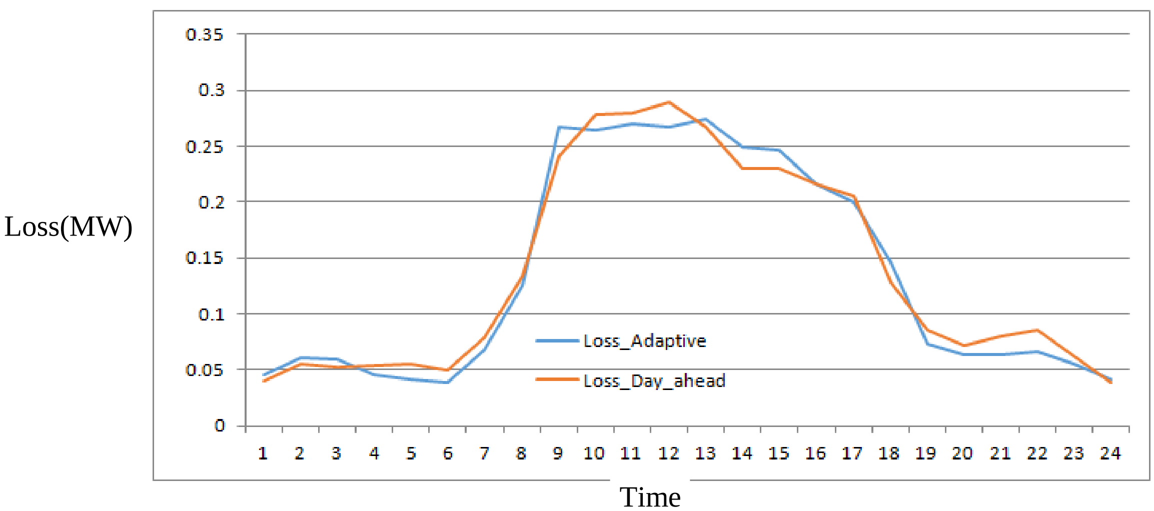


Figure 4-9 Comparison of loss profile between Day -Ahead and Adaptive (6 hour) forecasted solar and wind profile

Data	Adaptive	Day Ahead
Total Loss	3.2459	3.3036

Table 9 Loss Comparison between Adaptive and Day - Ahead Control

control updates the switching operation every 6 hours. As the simulation proceeds with time forecasted the data gets better. For instance at the first hour the decision taken for the capacitors and OLCT are applicable for the first six hours. However for the second six hours the controller has an opportunity to modify its switching order based on better forecasted data. It increases the accuracy for switching as shown is table 4-3. Figure 4-8 and Figure4-9 give the comparison between the adaptive and day- ahead control mode. Surely the adaptive one gives better voltage and loss profile.

4.7 Result Summary

Genetic algorithm gives more space to deal with our Volt/Var control problem compared to the fuzzy-based control. Putting a number of operations as a constraint generated acceptable outputs, which lacks in literature. In the simulation of test case1 it is found that DGs have a significant effect on the voltage profiles of the network. But without any coordination any acceptable condition might occur. In test case 2, the effect of DG on the number of switching of capacitors was presented. It is very clear that the random behavior of DG can increase the number of switching drastically without coordination. According to the proposed method, results are generated in test case 3. Here it is demonstrated how genetic algorithm based controllers with proper coordination kept the voltage profile and number of operation for OLTC and SCs within the limit. The proposed method works with 24 hours forecasted DG data while generating output. To verify the efficiency, voltage and loss profiles were later generated with actual DG output. After comparison it is found that the loss is still comparable. However to reduce the losses adaptive control was introduced. Taking decision for the next 24 hours every 6th hour can ensure more accurate DG output. Losses decreased when adaptive control is used instead of day-ahead control as shown in test case 4.

If results obtained from chapter three and four are compared it can be said that fuzzy and GA based optimal dispatch methods proposed in this thesis are different in terms of implementation procedure. Both have some benefits and drawback. Fuzzy logic based and genetic based algorithms were simulated in MATLAB simulation program designed for volt/var control. Both fuzzy and GA based methods keep the bus voltage within the limit and reduce down switching operation of OLTC and SC. The proposed GA based algorithms performs better than the proposed fuzzy based algorithm. Fuzzy based optimization method is dependent on the fuzzy rules given prior to modeling the system. DGs unpredictable nature is expected and covered by these rules. This method is effective when there are less components in the network. With the increasing number of components complexity increases. This method work in decentralized manner and for larger system network zoning should be introduced. In the proposed method using fuzzy in this thesis, the switching operation is reduced down after co-ordination. However the number of operation occurred in a day is still more than permissible. Genetic algorithm is known for not getting trapped in local minima. Genetic algorithm based method not only reduces the switching operation but also keeps it within the allowed for a single day. Moreover, adaptive control gives better loss profile.

Chapter 5
Conclusion and Future Work

5.1 Conclusion

This thesis presents two Volt/Var control techniques. The first one is fuzzy-based control which is meant to reduce the number of tap operations for the OLTC and to find the optimal switching for capacitors in a radial distribution system with DGs. Rule based fuzzy algorithm was developed to model the problem. Matlab/ Simulink was used to test the 8 bus systems and validate the proposed method. In the second approach a genetic algorithm based Volt/Var control technique is implemented to optimally dispatch OLTC and SC for a 24-hour period. To achieve this goal day-ahead control and adaptive control were applied to see the difference. The problem was first presented as a mathematical model of the objective function. The optimization problem was formulated to include an objective function that has to be minimized. Required nonlinear constraints were added in the form of boundary equations. A GA-based optimization algorithm was executed after Newton-Raphson load flow was carried out for the test system. The algorithm was tested in MATLAB 2014 version on the 30-bus test distribution system.

5.2 Contribution

In previous literature, researchers have focused on various aspects of the problem of increasing the penetration of distributed generation. The aspects of voltage increase, reactive power control and dispatch, and optimal generation were discussed in previous works. The beneficiaries of this work include increments of lifetime of OLTC and SC as their number of operations get highest priory here. Proposed methods can reduce the number of operations for both OLTC and SC. Additionally, voltage and reactive power controller introduced in this work will eventually benefit the final consumer of power, be it residential, commercial or industrial. The end user benefits from the better voltage profile introduced by the voltage controller as described in the research work.

In this thesis work, objectives set in chapter two are satisfied by running simulation in two different test systems. In chapter three, is has been verified using 8 bus distribution network that DGs can put significant effect on number of operation of OLTC. Besides that the benefit of coordination among DG,OLTC and SC is verified in a decentralized control manner. In chapter four, impact of DGs on number of operation in SC has been demonstrated. In the same chapter impact of DGs in voltage and loss profile is demonstrated. Using a centralized GA based control DGs impact remained within acceptable limits after coordination among OLTC, SC and DGs. Besides that it is also shown that a time based adaptive control is better to improve voltage and loss profile.

From test results of fuzzy multi-agent based control, it is found that voltages are within the boundary using fuzzy controllers. Efficient control has been achieved by the coordination of all the voltage and reactive power control devices (OLTC, SC) with the DGs. Decentralized control using multi-agent and proper incorporation of fuzzy logic reduced calculation burden for each control devices. This method is less complex and automated for regulation purposes.From the results obtained from GA based optimization, it is seen that with adaptive control, it is possible to improve the voltage and loss profile. This has been achieved by dispatching transformers and SC optimally. In addition, the controller can be modified to include multiple objectives. This could include others aspects affecting Volt/Var control.

5.3 Future Work

The methods proposed in this thesis are either tested using an 8 bus or 30 bus system. Feasibilities for large test systems are yet to be verified. Again with large network controllers, modification and zoning can be introduced to avoid complexity. Large-scale optimization would take a long time when using the controller in its current form. The continuous operation of OLTC and SC are also shown in this thesis. But in practice, OLTC needs time to go to one step to another. Also in the second method a fixed value of capacitors is taken. Instead of fixed value, considering the use of capacitor banks will be more acceptable. Furthermore, the controller in this research assumes continuous operation of OLTCs and shunt capacitors.

Appendix A
Information of 30 Bus Distribution System

Base Values Base voltage along the main distribution feeder is 22 kV. Chosen base capacity to be 100MVA, and the following table shows all the base values that are used.

Base	Value
Vbase(KV)	22
Sbase(MVA)	100
Zbase	21

Table 10 Base values for 30 bus System

Loads

24 hour real load profile data is used for simulation. Maximum load values are given as below at any hour of the day.

Bus	P(MW)	Q(MVAR)
1	0	0
2	0.522	0.174
3	0	0
4	0.936	0.312
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0.189	0.063
11	0.336	0.112
12	0.657	0.219
13	0.783	0.261
14	0.729	0.261
15	0.477	0.159
16	0	0
17	0.549	0.183
18	0.477	0.159
19	0.432	0.144
20	0.572	0.224
21	0.495	0.165
22	0.207	0.069
23	0.522	0.174
24	0.2917	0.639
25	1.116	0.372

26	0.549	0.183
27	0.792	0.264
28	0.882	0.294
29	0.882	0.294
30	0.882	0.294

Table 11 Loads at buses

Line Parameters:

From	To	R(p.u)	X(p.u)
0	1	0.11	0.32
1	2	0.05	0.5
2	3	0.07	0.07
3	4	0.22	0.19
4	5	0.1	0.09
5	6	0.31	0.18
6	7	0.26	0.14
7	8	0.26	0.14
8	9	0.25	0.14
9	10	0.25	0.14
10	11	0.75	0.42
11	12	0.35	0.2
12	13	0.14	0.08
13	14	0.29	0.16
8	15	0.09	0.08
15	16	0.14	0.08
16	17	0.25	0.14
6	18	0.09	0.08
18	19	0.3	0.26
19	20	0.29	0.16
6	21	0.11	0.1
3	22	0.11	0.11
22	23	0.06	0.06
23	24	0.11	0.09
24	25	0.28	0.24
25	26	0.2	0.17
26	27	0.29	0.16
1	28	0.09	0
28	29	0.31	0.17
29	30	0.21	0.12

Table 12 Line Parameters

Appendix B

MATLAB Code for Genetic Algorithm Based Volt/Var Control for Optimal Dispatch of OLTC and SC

%%SYSTEM DATA

```
function mpc =case30(seq,cap1,cap2,cap3,cap4,cap5,cap6,tap)  ;
 if cap1==1
     c1=0.6
 else c1=0
 end
 if cap2==1
     c3=0.6
 else c3=0
 end
 if cap3==1
     c4=0.6
 else c4=0
 end
  if cap4==1
      c5=0.3
 else c5=0
 end
 if cap5==1
     c6=0.9
 else c6=0
 end
 if cap6==1
     c7=0.9
 else c7=0
 end
global PL2_day;global QL2_day;global PL4_day;global QL4_day;global
PL9_day;
global QL9_day;global PL11_day;global QL11_day;global PL12_day;
global QL12_day;global PL13_day;global QL13_day;global PL14_day;
global QL14_day;global PL15_day;global QL15_day;global PL16_day;
global QL16_day;global PL17_day;global QL17_day;global PL18_day;
global QL18_day;global PL19_day;global QL19_day;global PL21_day;
global QL21_day;global PL22_day;global QL22_day;global PL23_day;
global QL23_day;global PL20_day;global QL20_day;global PL25_day;
global QL25_day;global PL26_day;global QL26_day;global PL27_day;
global QL27_day;global PL28_day;global QL28_day;global PL30_day;
global QL30_day;global day;
mpc.version = '2';
w=1;
%%-----  Power Flow Data  -----%%
%% system MVA base
mpc.baseMVA = 100;
global DG_wind4_hour1;global DG_wind4q_hour1; global DG_wind3_hour1;
global DG_wind3q_hour1; global DG_wind2_hour1;global DG_wind2q_hour1;
 global DG_wind1_hour1;global DG_wind1q_hour1; global DG_solar1_hour1;
```

```
global DG_solar2_hour1; s1=DG_solar1_hour1(seq); s2=DG_solar2_hour1(seq);
 w1=DG_wind1_hour1(seq); w1q=DG_wind1q_hour1(seq); w2=DG_wind2_hour1(seq);
 w2q=DG_wind2q_hour1(seq); w3=DG_wind3_hour1(seq);
w3q=DG_wind3q_hour1(seq);
 w4=DG_wind4_hour1(seq); w4q=DG_wind4q_hour1(seq);
mpc.bus = [
            1   2   0                   0                       0   0 ...
            1   1   0   23  1   1.2 0.95;
            2   1   w*PL2_day(seq)      w*QL2_day(seq)-c1       0   0 ...
            1   1   0   23  1   1.2     0.65;
            3   1   0                   0                       0   0 ...
            1   1   0   23  1   1.2 0.65;
            4   1   w*PL4_day(seq)      w*QL4_day(seq)          0   0 ...
            1   1   0   23  1   1.2 0.65;
            5   1   0                   0                       0   0 ...
            1   1   0   23  1   1.2 0.65;
            6   1   0                   0                       0   0 ...
            1   1   0   23  1   1.2 0.65;
            7   1   0                   0                       0   0 ...
            1   1   0   23  1   1.2 0.65;
            8   1   0                   0                       0   0 ...
            1   1   0   23  1   1.2 0.65;
            9   1   w*PL9_day(seq)      w*QL9_day(seq)          0   0 ...
            1   1   0   23  1   1.2 0.65;
            10  1   0                   0                       0   0 ...
            3   1   0   23  1   1.2 0.65;
            11  1   w*PL11_day(seq)-w1  w*QL11_day(seq)+w1q     0   0 ...
            1   1   0   23  1   1.2 0.65;
            12  1   w*PL12_day(seq)     w*QL12_day(seq)         0   0 ...
            2   1   0   23  1   1.2 0.65;
            13  1   w*PL14_day(seq)     w*QL14_day(seq)-c3      0   0 ...
            2   1   0   23  1   1.2     0.65;
            14  1   w*PL14_day(seq)     w*QL14_day(seq)         0   0 ...
            2   1   0   23  1   1.2 0.65;
            15  1   w*PL15_day(seq)-s1  w*QL15_day(seq)-c4      0   0 ...
            2   1   0   23  1   1.2 0.65;
            16  1   w*PL16_day(seq)     w*QL16_day(seq)         0   0 ...
            2   1   0   23  1   1.2 0.65;
            17  1   w*PL17_day(seq)     w*QL17_day(seq)         0   0 ...
            2   1   0   23  1   1.2 0.65;
            18  1   w*PL18_day(seq)-s2  w*QL18_day(seq)         0   0 ...
            2   1   0   23  1   1.2 0.65;
            19  1   w*PL19_day(seq)     w*QL19_day(seq)-c5      0   0 ...
            2   1   0   23  1   1.2 0.65;
            20  1   w*PL20_day(seq)     w*QL20_day(seq)         0   0 ...
            2   1   0   23  1   1.2 0.65;
            21  1   w*PL21_day(seq)-w2  w*QL21_day(seq)+w2q     0   0 ...
            3   1   0   23  1   1.2 0.65;
            22  1   w*PL22_day(seq)     w*QL22_day(seq)         0   0 ...
            3   1   0   23  1   1.2     0.65;
            23  1   0                   0-c6                    0   0 ...
            2   1   0   23  1   1.2     0.65;
            24  1   w*PL23_day(seq)-w4  w*QL23_day(seq)+w4q     0   0 ...
```

```
            3   1   0   23  1   1.2 0.65;
            25  1   w*PL25_day(seq)     w*QL25_day(seq)-c7      0   0 ...
            3   1   0   23  1   1.2 0.65;
            26  1   w*PL26_day(seq)     w*QL26_day(seq)         0   0 ...
            3   1   0   23  1   1.2 0.65;
            27  1   w*PL27_day(seq)     w*QL27_day(seq)         0   0 ...
            3   1   0   23  1   1.2     0.65;
            28  1   w*PL28_day(seq)-w3  w*QL28_day(seq)+w3q     0   0 ...
            1   1   0   23  1   1.2 0.65;
            29  1   w*PL30_day(seq)     w*QL30_day(seq)         0   0 ...
            3   1   0   23  1   1.2 0.65;
            30  1   w*PL30_day(seq)     w*QL30_day(seq)         0   0 ...
            3   1   0   23  1   1.2 0.65;
];

mpc.gen = [
    1   10                  0   0       0   1   100 1   1
0   0   0   0   0   0   0   0   0   0   0   0;
    22  0                   0   0       0   0   100 0   0
0   0   0   0   0   0   0   0   0   0   0   0;
    28  0                   0   0       0   0   100 0   0
0   0   0   0   0   0   0   0   0   0   0   0;
    27  26.91               0   48.7 -15    1   100 0   55
0   0   0   0   0   0   0   0   0   0   0   0;
    23  19.2                0   40   -10    1   100 0   30
0   0   0   0   0   0   0   0   0   0   0   0;
    13  37                  0   44.7 -15    1   100 0   40
0   0   0   0   0   0   0   0   0   0   0   0;
];
mpc.branch = [
    1   2   0.11    0.32    0       130 130 130 tap 0   1   -360    360;
    2   3   0.07    0.07    0       130 130 130 0   0   1   -360    360;
    3   4   0.22    0.19    0       65  65  65  0   0   1   -360    360;
    4   5   0.10    0.09    0       130 130 130 0   0   1   -360    360;
    5   6   0.31    0.18    0       130 130 130 0   0   1   -360    360;
    6   7   0.26    0.14    0       65  65  65  0   0   1   -360    360;
    7   8   0.26    0.14    0       90  90  90  0   0   1   -360    360;
    8   9   0.25    0.14    0       70  70  70  0   0   1   -360    360;
    9   10  0.25    0.14    0       130 130 130 0   0   1   -360    360;
    10  11  0.75    0.42    0       32  32  32  0   0   1   -360    360;
    11  12  0.35    0.20    0       65  65  65  0   0   1   -360    360;
    12  13  0.14    0.08    0       32  32  32  0   0   1   -360    360;
    13  14  0.29    0.16    0       65  65  65  0   0   1   -360    360;
    8   15  0.09    0.08    0       65  65  65  0   0   1   -360    360;
    15  16  0.14    0.08    0       65  65  65  0   0   1   -360    360;
    16  17  0.25    0.14    0       65  65  65  0   0   1   -360    360;
    6   18  0.09    0.14    0       32  32  32  0   0   1   -360    360;
    18  19  0.30    0.08    0       32  32  32  0   0   1   -360    360;
    19  20  0.29    0.26    0       32  32  32  0   0   1   -360    360;
    6   21  0.11    0.16    0       16  16  16  0   0   1   -360    360;
    3   22  0.11    0.10    0       16  16  16  0   0   1   -360    360;
    22  23  0.06    0.06    0       16  16  16  0   0   1   -360    360;
    23  24  0.11    0.09    0       16  16  16  0   0   1   -360    360;
```

```
    24   25   0.28     0.24     0        32   32   32   0    0    1    -360     360;
    25   26   0.20     0.17     0        32   32   32   0    0    1    -360     360;
    26   27   0.29     0.16     0        32   32   32   0    0    1    -360     360;
    2    28   0.09     0.00     0        32   32   32   0    0    1    -360     360;
    28   29   0.31     0.17     0        32   32   32   0    0    1    -360     360;
    29   30   0.21     0.12     0        32   32   32   0    0    1    -360     360;

];
```

%% FITNESS FUNCTION

```
function y=fitness(x)
 p = 0;
 global Simu_Hour;


    for j = 1:Simu_Hour

    tap=1+0.0125*x(144+j);
    temp=case30(j+12,x(j),x(24+j),x(48+j),x(72+j),x(96+j),x(120+j),tap);
    T=runpf(temp);
        for b=1:29
        p=p+T.branch(b,14)+T.branch(b,16);
        end

    end
y=p;
```

%% CONSTRAINTS FUNCTION

```
function [c, ceq]=constraints(x)
global Simu_Hour;
tap_num=0;c1_tap=0;c2_tap=0;c3_tap=0;c4_tap=0;c5_tap=0;c6_tap=0;
for j = 1:Simu_Hour-1
       if x(144+j)~=x(145+j)
       tap_num=tap_num+1   ;
       else
       end

if (x(j)~=x(j+1))
c1_tap= c1_tap+1;
else
end

if (x(24+j)~=x(25+j))
c2_tap= c2_tap+1;
else
end

if (x(48+j)~=x(49+j))
c3_tap= c3_tap+1;
else
end
```

```
if (x(72+j)~=x(73+j))
c4_tap= c4_tap+1;
else
end

if (x(96+j)~=x(97+j))
c5_tap= c5_tap+1;
else
end

if (x(120+j)~=x(121+j))
c6_tap= c6_tap+1;
else
end
end % for loop end

  V_day=zeros(1,24);
  Vmax=zeros(1,24);
  Vmin=zeros(1,24);
    for j = 1:Simu_Hour
        tap=1+0.0125*x(144+j);

temp=case30(j+12,x(j),x(24+j),x(48+j),x(72+j),x(96+j),x(120+j),tap);
        T=runpf(temp);
        for b=1:29
               V_day(b)=T.bus(b,8);
        end
         Vmax(j)=max(V_day);
         Vmin(j)=min(V_day);
     end
   vol=[-1*Vmin(1)-(-0.95); Vmax(1)-1.05;...
       -1*Vmin(2)-(-0.95); Vmax(2)-1.05;...
       -1*Vmin(3)-(-0.95); Vmax(3)-1.05;...
       -1*Vmin(4)-(-0.95); Vmax(4)-1.05;...
       -1*Vmin(5)-(-0.95); Vmax(5)-1.05;...
       -1*Vmin(6)-(-0.95); Vmax(6)-1.05;...
       -1*Vmin(7)-(-0.95); Vmax(7)-1.05;...
       -1*Vmin(8)-(-0.95); Vmax(8)-1.05;...
       -1*Vmin(9)-(-0.95); Vmax(9)-1.05;...
       -1*Vmin(10)-(-0.95); Vmax(10)-1.05;...
       -1*Vmin(11)-(-0.95); Vmax(11)-1.05;...
       -1*Vmin(12)-(-0.95); Vmax(12)-1.05;...
       -1*Vmin(13)-(-0.95); Vmax(13)-1.05;...
       -1*Vmin(14)-(-0.95); Vmax(14)-1.05;...
       -1*Vmin(15)-(-0.95); Vmax(15)-1.05;...
       -1*Vmin(16)-(-0.95); Vmax(16)-1.05;...
       -1*Vmin(17)-(-0.95); Vmax(17)-1.05;...
       -1*Vmin(18)-(-0.95); Vmax(18)-1.05;...
       -1*Vmin(19)-(-0.95); Vmax(19)-1.05;...
       -1*Vmin(20)-(-0.95); Vmax(20)-1.05;...
       -1*Vmin(21)-(-0.95); Vmax(21)-1.05;...
       -1*Vmin(22)-(-0.95); Vmax(22)-1.05;...
```

```
        -1*Vmin(23)-(-0.95); Vmax(23)-1.05;...
        -1*Vmin(24)-(-0.95); Vmax(24)-1.05;...
        ];
capacitor_swtching = [
    c1_tap - 7;...
    c2_tap - 7;...
    c3_tap - 7;...
    c4_tap - 7;...
    c5_tap - 7;...
    c6_tap - 7
    tap_num-12];

  % All nonlinear constraints
c = [vol;capacitor_swtching];
 % No equality constraints
ceq = [];

%%MAIN FUNCTION
% nvars = 240;
 nvars = 168;
 LB=[0  0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
...
     0  0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
...
     0  0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
...
     0  0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
...
     0  0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
...
     0  0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
...
     0  0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
...
     0  0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
...
     -8 -8  -8  -8  -8  -8  -8  -8  -8  -8  -8  -8  -8  -8  -8  -8  -8  -8
...
     -8 -8  -8  -8  -8  -8];
 UB=[1  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
...
     1  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
...
     1  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
...
     1  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
...
     1  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
...
     1  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
...
     1  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
...
```

```
     1  1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
...
     8  8   8   8   8   8   8   8   8   8   8   8   8   8   8   8   8   8
...
     8  8   8   8   8   8
];
ObjectiveFunction = @fitness;
ConstraintFunction = @constraints;

opts = gaoptimset(...
    'PopulationSize', 300, ...
    'Generations', 600, ...
    'EliteCount', 20, ...
    'StallGenLimit' ,400,...
    'TolFun', 1e-8, ...
    'PlotFcns',@gaplotbestf);
  [x, fbest, exitflag] = ga(ObjectiveFunction, nvars, [], [], [], [], ...
    LB, UB, ConstraintFunction,1:168, opts);

display(x);
```

Bibliography

[1] P. H. R. P. Gama; E. M. Flores; G. P. Alvarez; J. Mak; N. J. Guaraldo; E. C. Guardia – B&G Pesquisa D. S. Filho; A. V. Barbosa; B. F. Soares; A. C. Q. Messora; S. Sanzoni - Bandeirante Energia S.A, "INCORPORATING DISTRIBUTED GENERATION IN THE ENERGY CONTRACTING STRATEGY IN A REGULATED ENVIRONMENT", Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium, 29-31 July 2009.

[2] Wang Bo and Lan Ka, "Analysis of the distributed generation system and the influence on power loss," Power and Energy Engineering Conference (APPEEC), 2011 Asia-Pacific, 25-28 March 2011.

[3] N. Jenkins, "Embedded Generation Tutorial", Power Engineering Journal, pp. 145 – 150, June 1995.

[4] D.S. Henderson," Synchronous or Induction Generators? – The Choice for Small Scale Generation", in Proc. of Opportunities and Advances in International Power Generation, 1996.

[5] M.W. Davis, "Microturbines – an economics and reliability evaluation for commercial, residential and remote load applications", IEEE Transaction on Power Systems, vol. 14, no. 4, pp. 1556-1562, 1999.

[6] FERRY AUGUST VIAWAN,"]Voltage Control and Voltage Stability of Power Distribution Systems in the Presence of Distributed Generation" CHALMERS UNIVERSITY OF TECHNOLOGYGöteborg, Sweden 2008 in IEEE Power and Energy Society General Meeting, Pittsburgh, 2008, pp. 1-6

[7]Yue Shi,"An Investigation of Volt/Var Control on FREEDM Systems" Raleigh, North Carolina 2014

[8]T.A. Short, "Distributed Generation," in Electric Power Distribution Handbook.: CRC Press LLC, 2004.

[9] IEEE Application Guide for IEEE Std 1547(TM), IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems, IEEE Standard 1547.2-2008, 2009

[10] Andren, F.; Bletterie, B.; Kadam, S.; Kotsampopoulos, P.; Bucher, C., "On the Stability of local Voltage Control in Distribution Networks with a High Penetration of Inverter-Based Generation," Industrial Electronics, IEEE Transactions on , vol.PP, no.99, pp.1,1

[11]J. J. Grainger and S. Civanlar, "Volt/Var Control on distribution Systems with lateral branches using shunt capacitors and voltage regulators Part I: The overall problem," IEEE Transactions on Power Apparatus and Systems, vol. 11, pp. 3278-3283, 1985.

[12]Mats Larsson, "Coordinated Voltage Control in Electric Power Systems," Lund University, Lund, Doctoral Dissertation ISBN 91-88934-17-9, 2000

[13] Turan Gönen, Electric Power Distribution System.: McGraw-Hill Book Company, 1986.A.G. Madureira and J.A. Peças Lopes, "Coordinated Voltage Support in Distribution Networks with Distributed Generation and Microgrids," IET Renewable Power Generation, vol. 3, no. 4, 2009.

[14]Lu,F._C and Hsu,Y.-Y"reactive power and votlage control in a distribution substaion using dynammic programming" IEE Proc. Gene. Trans. Dsitir., 1995,142(6),pp 639-645

[15] Philip P. Barker, R. W. (2000). Determining the Impact of Distributed Generation on Power Systems: Part 1 - Radial Distribution Systems. 12. IEEE. Retrieved 02 16, 2011, from IEEE.

[16]R. Shivarudraswamy and D. N. Gaonkar, "Coordinated Voltage Regulation of Distribution Network with Distributed Generators and Multiple Voltage-control Devices," Electric Power Components and Systems, vol. 40, no. 9, pp. 1072-1088, June 2012.

[17] J A Pecas Lopes, N Hatziargyriou, R Mutale, P Djapic, and P Jenkins, "Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities," Electric Power Systems Research, vol. 77, pp. 1189-1203, October 2006..

[18] C. L. Su, "Comparative Analysis of Voltage Control Strategies in Distribution Networks with Distributed Generation," in IEEE Power and Energy Society General Meeting, Calgary, AB, Canada, 2009.

[19] Philip P. Barker, R. W. (2000). Determining the Impact of Distributed Generation on Power Systems: Part 1 - Radial Distribution Systems. 12. IEEE. Retrieved 02 16, 2011, from IEEE.

[20] Raymond O'Gorman and Miles Redfern, "The Impact of Distributed Generation on Voltage Control in Distribution Systems," in 18th International Conference on Electricity Distribution, Turin, 2005.

[21] A. K. Kiprakis and A. R. Wallace, "Maximising energy capture from distributed generators in weak networks," , vol. 151, 2004, pp. 611-618.

[22] Thipnatee Sansawatt, Luis F Ochoa, and Gareth P Harrison, "Integrating Distributed Generation Using Decentralised Voltage Regulation," in IEEE Power and Energy Society General Meeting, Minneapolis, USA, 2010

[23] Panagis N Vovos, Aristides E. Kiprais, A. Robin Wallace, and Gareth P. Harrison, "Centralized and Distributed Voltage Control: Impact on Distributed Generation," IEEE Transactions on Power Systems, vol. 22, no. 1, pp. 476-483, February 2007.

[24] A Keane, L.F. Ochoa, E. Vittal, C.J. Dent, and G.P. Harrison, "Enhanced Utilization of Voltage Control Resources With Distributed Generation," IEEE Transactions on Power Systems, pp. 252-260, 2011.

[25] Yiyun Guo, Yufeng Lin, and Mingjie Sun, "The impact of integrating distributed generations on the losses in the smart grid," in 2011 IEEE Power and Energy Society General Meeting, 2011, pp. 1-6.

[26]Takao Tsuji, Tadaharo Goda, K Horiuchi, and Y Kojima, "Autonomous decentralized voltage profile control using multi-agent technology 76 considering time-delay," in IEEE Transmission & Distribution Conference & Exposition: Asia and Pacific, 2009, pp. 1-8.

[27]Li Yu, Dariusz Czarkowski, and Francisco de León, "Optimal distributed voltage regulation for secondary networks with DGs," IEEE Transactions on Smart Grid, vol. 3, no. 2, pp. 959-967, 2012

[28] Panagis N Vovos, Aristides E. Kiprais, A. Robin Wallace, and Gareth P. Harrison, "Centralized and Distributed Voltage Control: Impact on Distributed Generation," IEEE Transactions on Power Systems, vol. 22, no. 1, pp. 476-483, February 2007.

[29]C.M. Hird, H. Leite, and H. Li, "Network Voltage Controller for Distributed Generation," IEE Proceedings on Generation, Transmission & Distribution, vol. 151, no. 2, March 2004.

[30] M. Z. C. Wanik, Istvan Ehrlich, A. Mohamed, and H. Shareef, "Predictive VAR Management of Distributed Generators," in International Power & Energy Conference Proceedings, 2010, pp. 619-624.

[31] Ferry A. Viawan and Daniel Karlsson, "Coordinated Voltage and Reactive Power Control in the Presence of Distributed Generation," in IEEE Power and Energy Society General Meeting, Pittsburgh, 2008, pp. 1-6.

[32]A.G. Madureira and J.A. Peças Lopes, "Coordinated Voltage Support in Distribution Networks with Distributed Generation and Microgrids," IET Renewable Power Generation, vol. 3, no. 4, 2009.

[33] Luis Ochoa and Gareth P. Harrison, "Minimizing Energy Losses: Optimal Accomodation and Smart Operation of Renewable Distributed Geeneration," IEEE Transactions on Power Systems, vol. 26, no. 1, pp. 198-205, February 2011.

[34] A. A. Abou El Ela, M.A. Abido, and S.R. Spea, "Differential Evolutionary Algorithm for Optimal Reactive Power Dispatch," Electric Power Systems Research, vol. 81, pp. 458-464, 2010.

[35] Mohd Khairun Nizam Mohd Sarmin et al., "Coordinated Voltage Control in Distribution Network with Renewable Energy Based Distributed Generation," Engineering, vol. 5, no. 1B, pp. 208-214, January 2013.77

[36]Thierry van Cutsem and Gustavo Valverde, "Coordinated Voltage control of Distribution networks hosting dispersed generation," in 22nd International Conference on Electricity Distribution (CIRED), Stockholm, 2013.

[37] A.G. Madureira and J.A. Peças Lopes, "Coordinated Voltage Support in Distribution Networks with Distributed Generation and Microgrids," IET Renewable Power Generation, vol. 3, no. 4, 2009.

[38] Bauer, P. and de Haan, S. W. H. "Electronic tap changer for 500 kva/10 kv distribution transformers: design, experimental results and impact in distribution networks". In *Conference Record of 1998 Industry Applications Conference*, vol. 2, pp. 1530–7. IEEE.

[39] Cooke, G. H. and Williams, K. T. "New thyristor assisted diverter switch for on load transformer tap changers". *IEE Proceedings-Electric Power Applications*, vol. 139, no. 6, pp. 507–11.1992

[40] Carbone, F., Castellano, G. and Moreschini, G." Coordination and control of tap changers under load at different voltage level transformers". In *MELECON ’96* , vol. 3, pp. 1646–8. IEEE. 1996

[41] Yorino, N., Shuto, T., Nshimoto, H., Sasaki, H., Sugihara and Nakanishi, Y. "A distributed autonomous control method for TCUL transformers using fuzzy adaptive control scheme".

Transactions of the Institute of Electrical Engineers of Japan, vol. 119B, no. 12, pp. 1455–61. (1999).

[42] Grainger, J. J. and Civanlar, S. "volt/var control on distributions systems with lateral branches using shunt capacitors and voltage regulators: Parts IIII". *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, no. 11, pp. 3287–97.1988

[43] Roytelman, I., Wee, B. K., Lugtu, R. L., Kalas, T. M. and Brossart, T. "Pilot project to estimate the centralized volt/var control effectiveness". *IEEETransactions on Power Systems*, vol. 13, no. 3, pp. 864–9.1988

[44] Roytelman, I. and Ganesan, V. "Coordinated local and centralized control in distribution Management systems". *IEEE Transactions on Power Delivery*, vol. 15, no. 2, pp. 718–24. 2000

[45] Chang, C. S. and Huang, J. S. (1999). Centralized control of transformer tap changing for voltage stability enhancement. *Electric Machines And Power Systems*, vol. 27, no. 10, pp. 1041–54.

[46] Abe, S., Fukunaga, Y., Isono, A. and Kondo, B. (1982). Power system voltage stability. *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 10, pp. 3830–40.

[47] Liu, C.-C. and Vu, K. T. (1989). Analysis of tap-changer dynamics and construction of voltage stability regions. *IEEE Transactions on Power Systems*, vol. 36, no. 4, pp. 575–90.

[48] Medani´c, J., Ili´c-Spong, M. and Christensen, J. "Discrete models of slow voltage dynamics for under load tap-changing transformer coordination". *IEEE Transactions on Power Systems*, vol. 2, no. 4, pp. 873–82.19887

[49] Popovi´c, D. H., Hiskens, I. A. and Hill, D. J. " Investigations of load tap changer interaction". *International Journal of Electrical Power and Energy Systems*, vol. 18, no. 2, pp. 81–97.1996B

[50] Vu, K. T. and Liu, C.-C."Shrinking stability regions and voltage collapse in power systems." *IEEE Transactions on Circuits & Systems I-Fundamental Theory & Applications*, vol. 39, no. 4, pp. 271–89.1992

[51] Hiskens, I. A. and Hill, D. J."Dynamic interaction between tapping transformers". In *Proceedings of 11th Power Systems Computation Conference, Avignon, France*.1993

[52]Tamura, Y., Ogata, T., Motoyoshi, T., Tayama, Y. and Nakanishi, Y. "Interactions between regulating equipments in voltage instability environment". In *Proceedings of the 28th Conference on Decision and Control*, vol. 1, pp. 326–31. IEEE.1989

[53] Vu, K. T. and Liu, C.-C."Shrinking stability regions and voltage collapse in power systems". *IEEE Transactions on Circuits & Systems I-Fundamental Theory & Applications*, vol. 39, no. 4, pp. 271–89.1992

[54] Ohtsuki, H., Yokoyama, A. and Sekine, Y."Reverse action of on-load tap changer in association with voltage collapse". *IEEE Transactions on Power Systems*, vol. 6, no. 2, pp. 300–6.1991

[55] Medani´c, J., Ili´c-Spong, M. and Christensen, J."Discrete models of slow voltage dynamics for under load tap-changing transformer coordination". *IEEE Transactions on Power Systems*, vol. 2, no. 4, pp. 873–82.1987

[56] Yorino, N., Danyoshi, M. and Kitagawa, M."Interaction among multiple controls in tap change under load transformers". *IEEE Transactions on Power Systems*, vol. 12, no. 1, pp. 430–6.1997

[57] Vournas, C. D. and Van Cutsem, T."Voltage oscillations with cascaded load restoration". In *Stockholm Power Tech International Symposium on Electric Power Engineering*, vol. 5, pp. 173–8. IEEE.1995

[58]Wu, Q., Popovi´c, D. H. and Hill, D. J. "Avoiding sustained oscillations in power systems with tap changing transformers". *International Journal of Electrical Power & Energy Systems*, vol. 22, no. 8, pp. 597–605.2000

[59] T. N. Samuel and N. K. Nohria, "Digital control and instrumentation for step-voltage regulators," *IEEE Transactions on Power Apparatus and Systems*, vol. 104, pp. 194-199, 1985.

[60] W. H. Kersting, "Distribution feeder voltage regulation control," *IEEE Transactions on Industry Applications*, vol. 46, no. 2, pp. 620-626, 2010.

[61] A. A. Sallam and O. P. Malik, "Power factor improvement," in *Electric distribution systems*. Singapore: Jon Wiley & Sons IEEE Press, 2011, ch. 9, pp. 361-379.

[62] Y. V. Joshi, S. S. Deshpandm, and S. G. Kahaleka, "Microprocessor based automatic power factor control," in *Proceeding of IEEE TENCON*, Beijing, China, 1993, pp.326-329.

[63] T. B. Girotti, N. B. Tweed, and N. R. Houser, "Real-time VAR control by SCADA," *IEEE Transactions on Power Systems*, vol. 5, no. 1, pp. 61-64, 1990.

[64] M. E. Baran and Y. Hsu, "Volt/var control at distribution substations," *IEEE Transactions on Power Systems*, vol. 14, no. 1, pp. 312-318, 1999.

[65] S. J. Cheng, O. P. Malik, and G. S. Hope, "An expert system for voltage and reactive power control of a power system," *IEEE Transactions on Power Systems*, vol. 3, no. 4, pp. 1449-1455, 1988.

[66] M. M. A. Salama and A. Y. Chikhani, "An expert system for reactive power control of distribution system - Part 1: System configurations," *IEEE Transactions on Power Delivery*, vol. 7, no. 2, pp. 940-945, 1992.

[67] P. R. Laframbiose, G. Ferland, A. Y. Chikhani, and M. M. A. Salama, "An expert system for reactive power control of distribution system - Part 2: System implementation," *IEEE Transactions on Power Delivery*, vol. 10, no. 3, pp. 1433-1441, 1995.

[68] C. Pimpa and S. Premrudeepreechacharn, "Voltage control in power system using expert system based in SCADA system," in *Proceedings of IEEE Power and Energy Society Winter Meeting*, New York, NY, 2002, pp. 1282-1286.

[69] T.S. Abdel Salam, A.Y. Chikhani and R. Hackam, “A New Technique for Loss Reduction Using Compensating Capacitors Applied to Distribution System Varying Load Condition”, *IEEE Transactions on Power Delivery*, vol. 9, no. 2,April 1994.

[70] M.Y. Cho and Y.W. Chen, “Fixed/Switched Type Shunt Capacitor Planning of Distribution Systems by Considering Customer Load Patterns and Simplified Feeder Model”, *IEE Proc.-Gener, Transm, Distrib.*, vol. 144, no. 6, November1997.

[71] B. Milosevic and M. Begovic, “Capacitor Placement for Conservative Voltage Reduction on Distribution Feeders,” *IEEE Transactions on Power Delivery*, vol. 19, no. 3, July 2004.

[72] I. Roytelman and V. Ganesan, “Coordinated Local and Centralized Control in Distribution Management Systems”, *IEEE Transactions on Power Delivery*, vol. 15, no. 2, April 2000.

[73] V. Borozan, M.E. Baran and D. Novosel, “Integrated Volt/Var Control in Distribution Systems”, in *Proc. of IEEE Power Engineering Society Winter Meeting*, 2001.

[74] A. Augugliaro, L. Dusonchet, S. Favuzza and E.R. Sanseverino, “Voltage Regulation and Power Losses Minimization in Automated DistributionNetworks by an Evolutionary Multiobjective Approach”, *IEEE Transactions on Power Systems*, vol. 19, no.3, August 2004.

[75] Z. Hu, X. Wang, H. Chen and G.A. Taylor, “Volt/VAr Control in Distribution Systems Using a Time-Interval Based Approached”, *IEE Proc.-Gener, Transm, Distrib.*, vol. 150, no. 5, September 2003.

[76] R.H. Liang and C.K. Cheng, “Dispatch of Main Transformer ULTC and Capacitors in a Distribution System”, *IEEE Transaction on Power Delivery*, vol. 16, No. 4, October 2001.

[77] S. Civanlar and J.J. Grainger, “Forecasting Distribution Feeder Loads: Modelling and Application to Volt/VAr Control”, *IEEE Transaction on Power Delivery*, vol. 3, no. 1, January 1988.

[78] T. Senjyu, H. Takara, K. Uezato and T. Funabashi, “One-Hour-Ahead Load Forecasting Using Neural Network”, *IEEE Transaction on Power Systems,* vol. 17, no.1, February 2002.

[80]R. Baldick and F. F. Wu, "Efficient integer optimization algorithms for optimal coordination of capacitors and regulators," *IEEE Transactions on Power Systems*, vol. 5, no. 3, pp. 805-812, 1990.

[81]F. C. Lu and Y. Y. Hsu, "Reactive power/voltage control in a distribution substation using dynamic programming," *IEE Proceedings - Generation, Transmission and Distribution* , vol. 142, no. 6, pp. 639-645, 1995.

[82] I. Roytelman, B. K. Wee, R. L. Lugtu, and T. M. Kulars, "Volt/var control algorithm for modern distribution management system," *IEEE Transactions on Power Systems* , vol. 10, no. 3, pp. 1454-1460, 1995

[83] de Souza, B.A.; de Almeida, A.M.F., "Multiobjective Optimization and Fuzzy Logic Applied to Planning of the Volt/Var Problem in Distributions Systems," *Power Systems, IEEE Transactions on* , vol.25, no.3, pp.1274,1281, Aug. 2010

[84] Zengqiang Mi; Fei Wang, "Substation Reactive Power and Voltage Control Using Fuzzy Control Theory," *Industrial and Information Systems, 2009. IIS '09. International Conference on* , vol., no., pp.417,420, 24-25 April 2009

[85] Ruey-Hsun Liang; Yung-Shuen Wang, "Fuzzy-based reactive power and voltage control in a distribution system," *Power Delivery, IEEE Transactions on* , vol.18, no.2, pp.610,618, April 2003

[86] Benhamida, F.; Souag, S.; Salhi, Y.; Graa, A.; Bendaoud, A.; Djehaf, M., "A Fuzzy Logic controller for reactive power and PQ bus voltage control," *Electric Power and Energy Conversion Systems (EPECS), 2013 3rd International Conference on* , vol., no., pp.1,6, 2-4 Oct. 2013

[87] Eremia, M.; Simon, P.; Petricica, D.; Gheorghiu, D., "Some aspects of hierarchical voltage-reactive power control," *Power Engineering Society Summer Meeting, 2001* , vol.2, no., pp.872,880 vol.2, 2001

[88] Thukaram, D.; Yesuratnam, G., "Fuzzy-expert approach for voltage-reactive power dispatch," *Power India Conference, 2006 IEEE* , vol., no., pp.8 pp.,, 0-0 0

[89] Rami, Guillaume; Tran-Uoc, Tuan.; Hadjsaid, Nouredine, "Fuzzy logic supervision and control of distributed generators," *Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on* , vol., no., pp.1,5, 6-9 June 2005

[90] Suzuki, O.; Minakawa, T.; Yokoyama, R.; Tanaka, H., "Advanced intelligent voltage control systems coordinating main and local power systems," *Power Tech, 2005 IEEE Russia* , vol., no., pp.1,6, 27-30 June 2005

[91] Shu Hongchun; Sun Xiangfei; Si Dajun, "Study of fuzzy controller for voltage and reactive power in substation using rough set theory," *Power System Technology, 2002. Proceedings. PowerCon 2002. International Conference on* , vol.4, no., pp.2452,2456 vol.4, 2002

[92] Ekel, P.Ya.; Terra, L.D.B.; Junges, M.F.D.; de Oliveira, F.J.A.; Melek, A.; Taguti, T.Y., "Fuzzy logic in voltage and reactive power control in regulated and deregulated environments," *Transmission and Distribution Conference and Exposition, 2001 IEEE/PES* , vol.1, no., pp.85,90 vol.1, 2001

[93] Ekel, P.Ya.; Terra, L.D.B.; Junges, M.F.D.; de Oliveira, F.J.A.; Kowaltschuk, R.; Taguti, T.Y., "Fuzzy logic in voltage and reactive power control in power systems," *Control Applications, 1999. Proceedings of the 1999 IEEE International Conference on* , vol.1, no., pp.622,627 vol. 1, 1999

[94] Zhang, W.; Liu, Y., "Fuzzy logic controlled particle swarm for reactive power optimization considering voltage stability," *Power Engineering Conference, 2005. IPEC 2005. The 7th International* , vol., no., pp.1,555, Nov. 29 2005-Dec. 2 2005

[95] Gitizadeh, M.; Karampour, H., "Multi-objective fuzzy based reactive power and voltage control in a distribution system using SA," *Hybrid Intelligent Systems (HIS), 2011 11th International Conference on* , vol., no., pp.334,339, 5-8 Dec. 2011

[96] Wang Qi; Zhu Lingzhi; Zhou Shuangxi, "A novel fuzzy logic secondary voltage controller," *Power System Technology, 2002. Proceedings. PowerCon 2002. International Conference on* , vol.4, no., pp.2589,2593 vol.4, 2002

[97] Wennan Lin; Yihua Li; Xingtao Xu; Maojun li, "Reactive power optimization in area power grid based on improved Tabu search algorithm," *Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference on* , vol., no., pp.1472,1477, 6-9 April 2008

[98] K. Iba, "Reactive power optimization by genetic algorithm," IEEE Trans. Power Systems, vol. 9(2),

pp. 685-692, 1994.

[99] K.Y. Lee, Y.M. Park, "Optimization method for reactive power planning by using a modified simple

genetic algorithm," IEEE Trans. Power Systems, vol. 10(4), pp. 1843-1850, 1995.

[100]W Yan, F. Liu, C.Y. Chung, KP Wong, "A hybrid genetic algorithm interior point method

for optimal reactive power flow," IEEE Trans. Power Systems, vol. 21(3), pp. 1163-1168,2006.

[101] P. Subbaraj, P.N. Rajnarayanan, "Optimal reactive power dispatch using self-adaptive real coded genetic algorithm," Electric Power System Research, vol. 7(2), pp. 374-381, Feb. 2009.

[102]G. Vlachogiannis, 1 Osterfaard, "Reactive power and voltage control based on general quantum

genetic algorithms," Expert systems with applications, vol. 36(3), pp. 6118-6126, Apr. 2009.

[103] Liu, S.C.; Zhang, J.H.; Liu, Z.Q.; Wang, H.Q., "Reactive power optimization and voltage control using an improved genetic algorithm," *Power System Technology (POWERCON), 2010 International Conference on* , vol., no., pp.1,5, 24-28 Oct. 2010

[104] Dong Guan; Zixing Cai; Zhizhou Kong, "Reactive power and voltage control using micro-genetic algorithm," *Mechatronics and Automation, 2009. ICMA 2009. International Conference on* , vol., no., pp.5019,5024, 9-12 Aug. 2009

[105] Malachi, Y.; Singer, S., "A genetic algorithm for the corrective control of voltage and reactive power," *Power Systems, IEEE Transactions on* , vol.21, no.1, pp.295,300, Feb. 2006

[106] Ying-Yi Hong; Yi-Feng Luo, "Reactive Power Control in Distribution System Using Genetic Algorithms," *Intelligent Systems Applications to Power Systems, 2007. ISAP 2007. International Conference on* , vol., no., pp.1,6, 5-8 Nov. 2007

[108] Abessi, A.; Vahidinasab, V.; Ghazizadeh, M.S., "Centralized Support Distributed Voltage Control by Using End-Users as Reactive Power Support," *Smart Grid, IEEE Transactions on* , vol.PP, no.99, pp.1,1

[109] Godwin Immanuel, D.; Chritober Asir Rajan, C., "An Genetic Algorithm approach for reactive power control problem," *Circuits, Power and Computing Technologies (ICCPCT), 2013 International Conference on* , vol., no., pp.74,78, 20-21 March 2013